# Collisionless GRB Shocks

## uncovering the underlying physics


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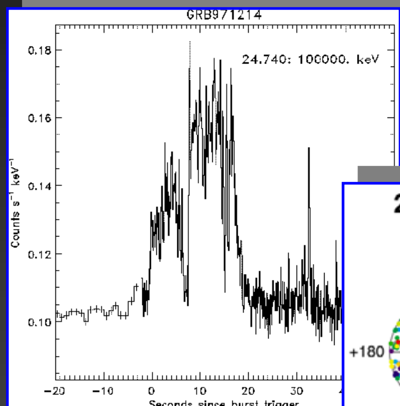
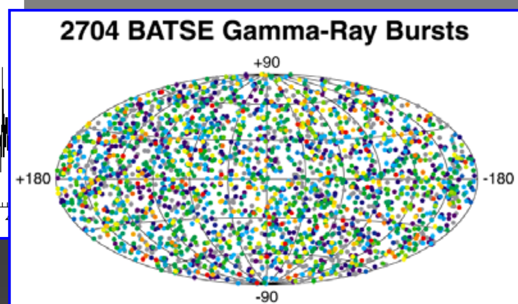
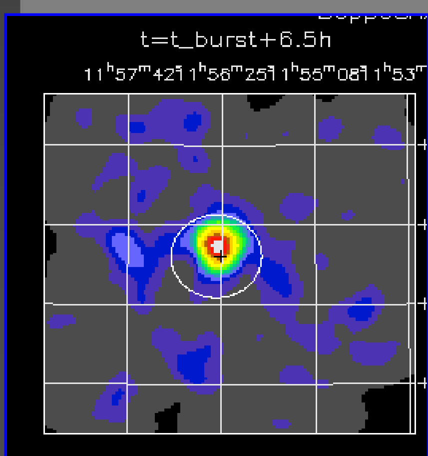
# Do we understand GRBs ?

**synchrotron shock model**




*$z \sim 1$*

$\downarrow$

*$E \sim 10^{54}$ erg (isotropic)*

*$t \sim 1$ sec*


Bravo Castle 15 Mt

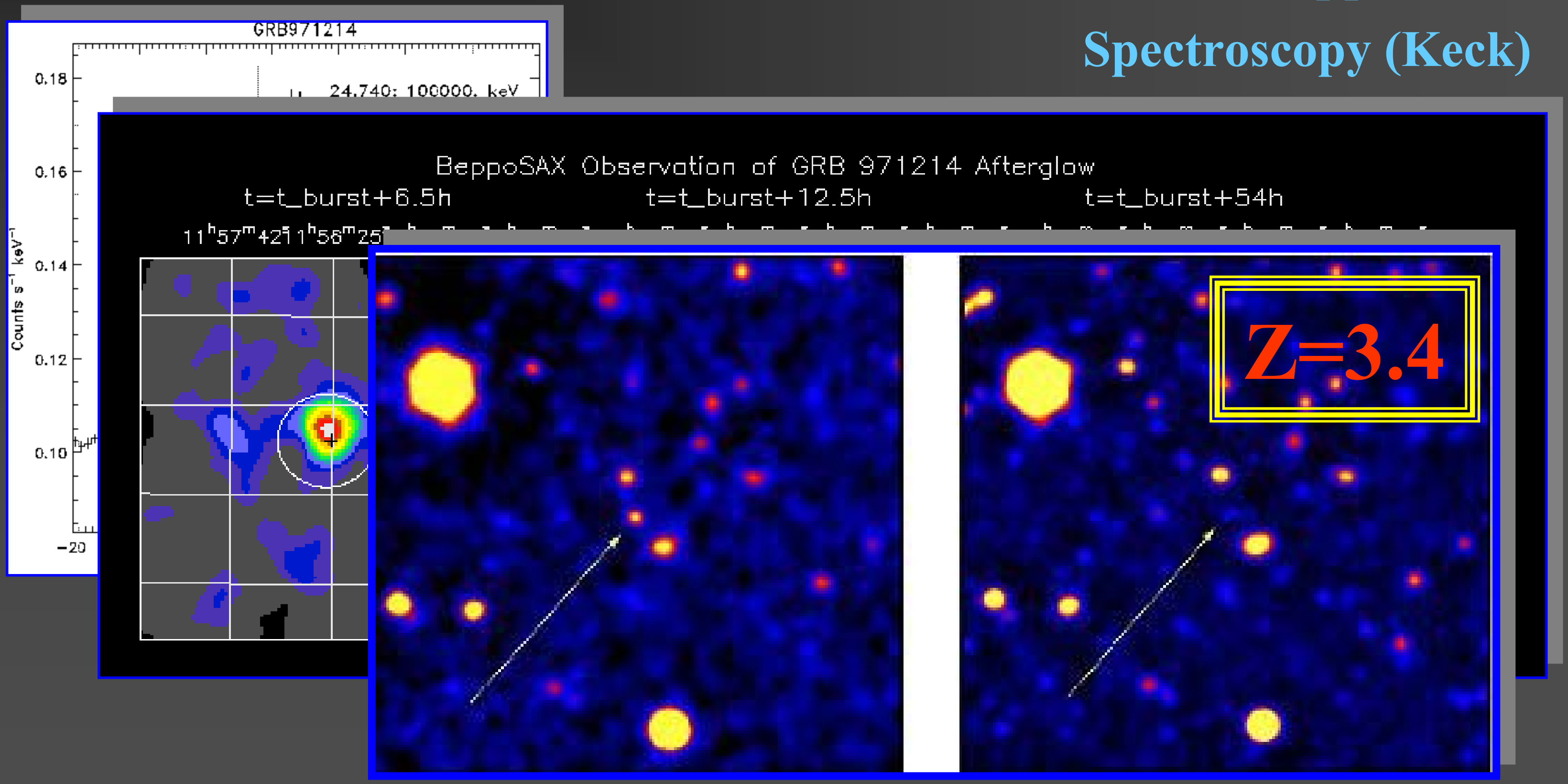
# Gamma-Ray Bursts

**GRBs are 10 billion light years away!!!**

**Burst trigger (BATSE) GRB 971214**

**Localization (Beppo-SAX)**

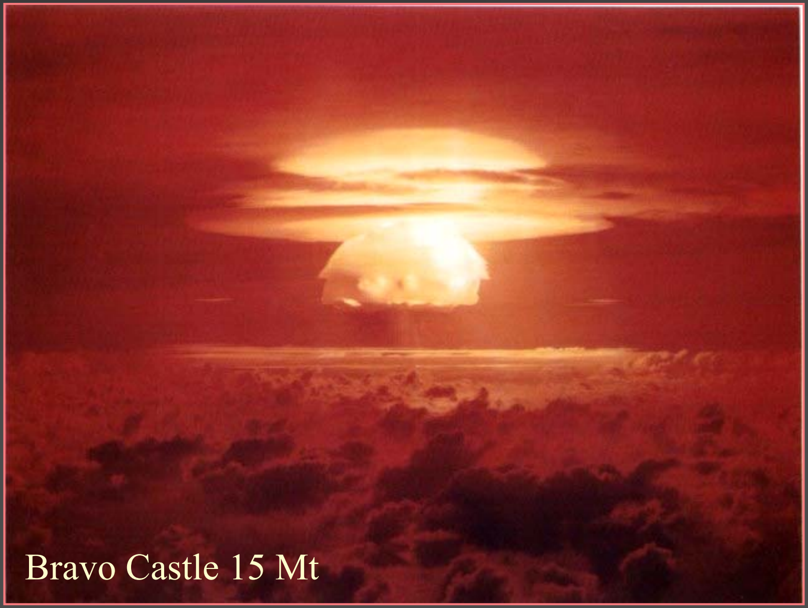
**Spectroscopy (Keck)**



# Energetics

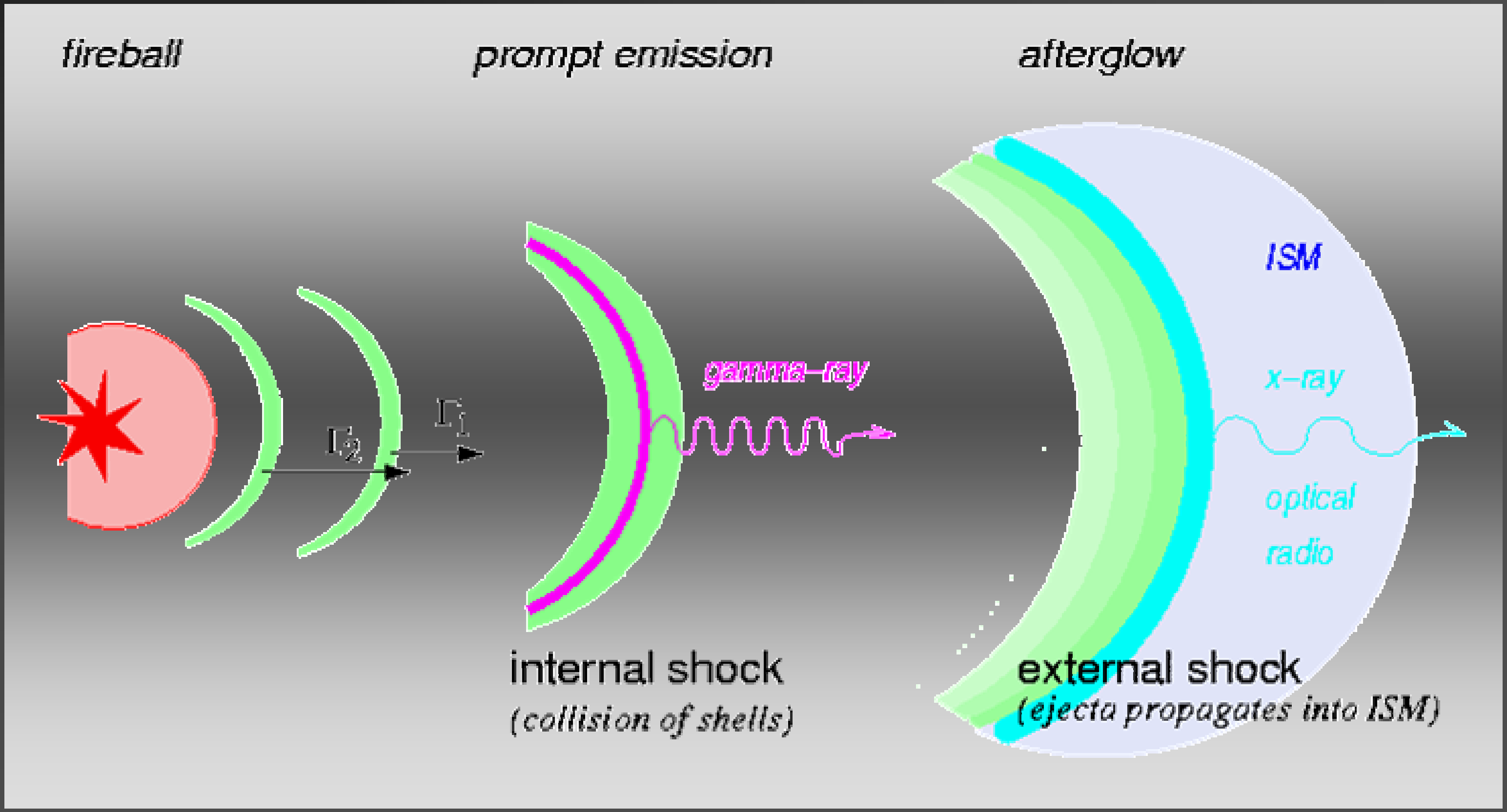
**Total energy** $= (\# \text{ photons/second/area}) * (\text{duration}) * (4\pi R^2)$
$= 10^{52} - 10^{54}$ erg $> M_{SUN}\, c^2$

*tremendous amount of energy is released within a second*



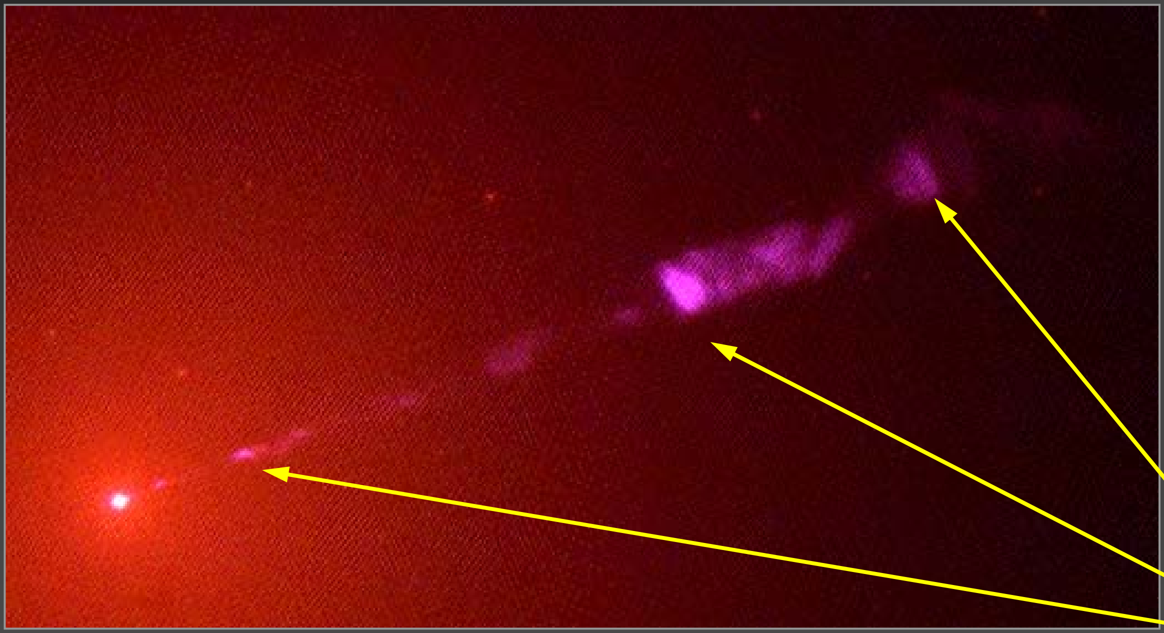
# "Standard Model"

## --- GRB Shock Model ---



# Shocks in Jets - Knots

**Jet from M87**

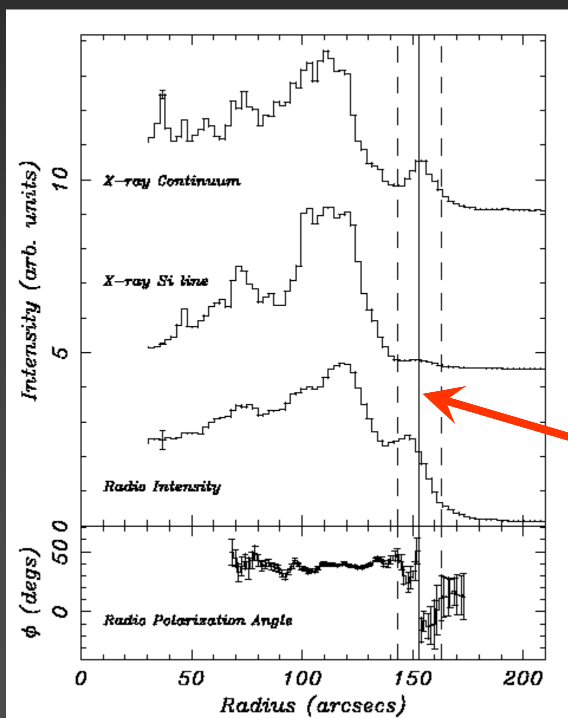


***knots***

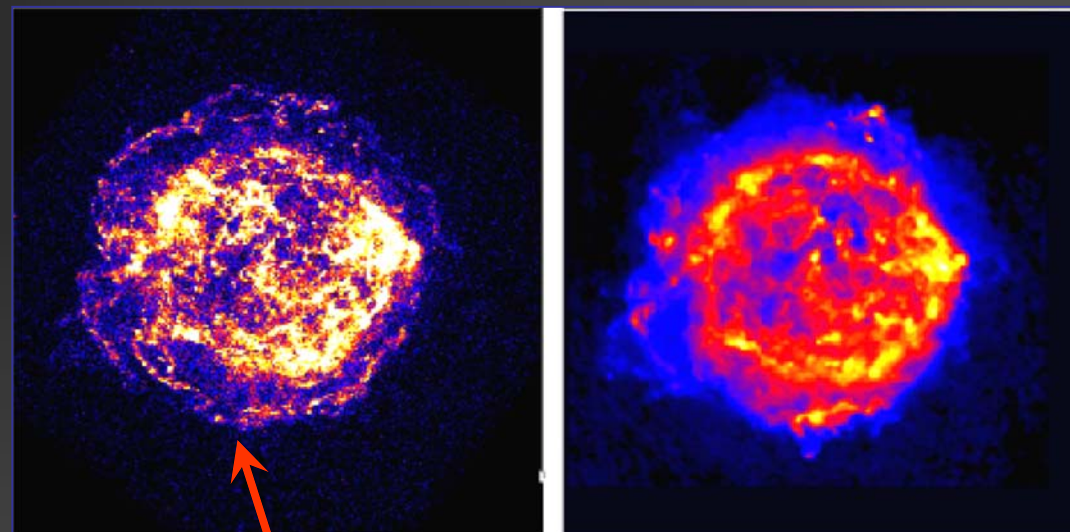
HST image

# Supernova Shock

## Cassiopea A




(Gotthelf, et al. 2001)



Chandra 2001 & VLA 1997 images

**forward shock**

# GRB Shock Model Postulates

- *Rankine-Hugoniot jump conditions*

+

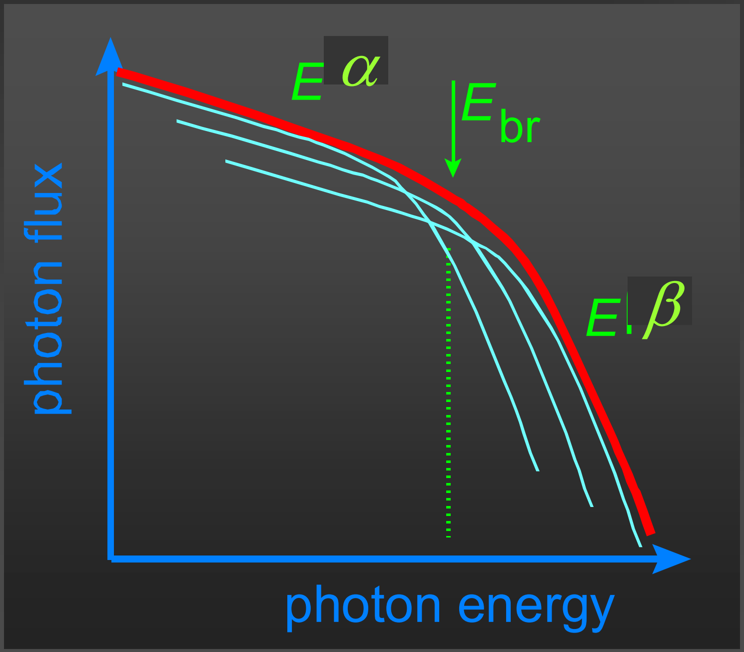
- *Near-equipartition magnetic fields*
- *Near-equipartition energy in electrons*

**Synchrotron radiation**

**Light curves**

# GRB Shock Model Prediction

**Predicted γ-ray spectrum**

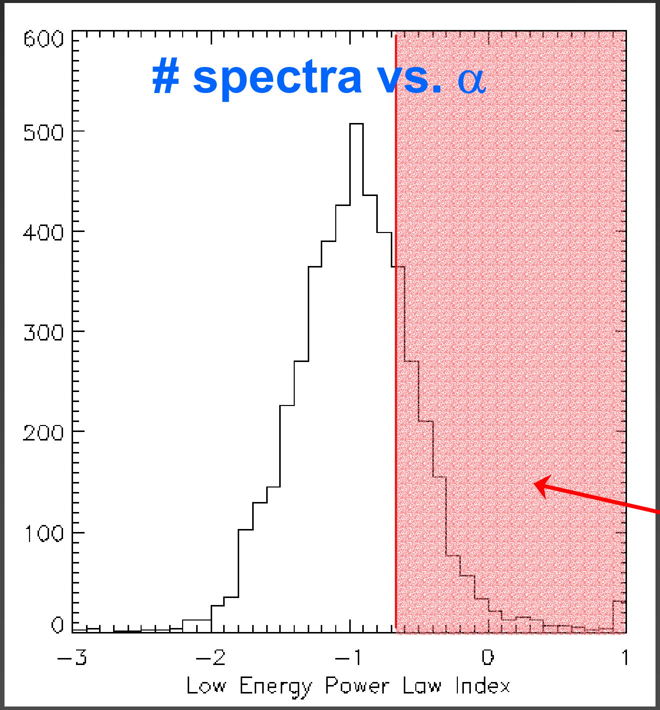



**Composite synchrotron**

- ***two power-laws***
- ***smooth break***
- ***$\alpha$ < -2/3***

# Warning signal #1

**Observed GRB spectra often agree with theory, but …**




**"Line of Death"**

spectra cannot be harder than $E^{-2/3}$ below break

**forbidden: $\alpha > -2/3$**

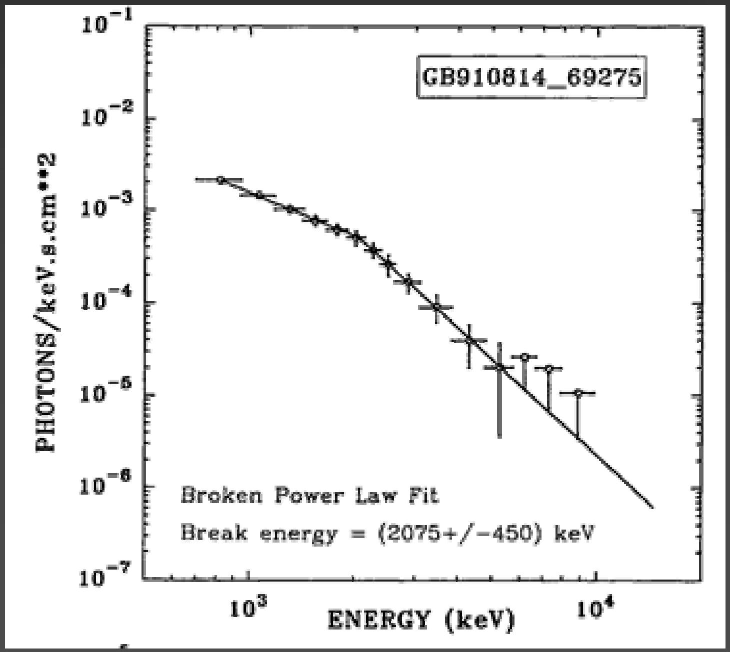
(Preece et al. 2000, ApJS)

# Warning signal #2

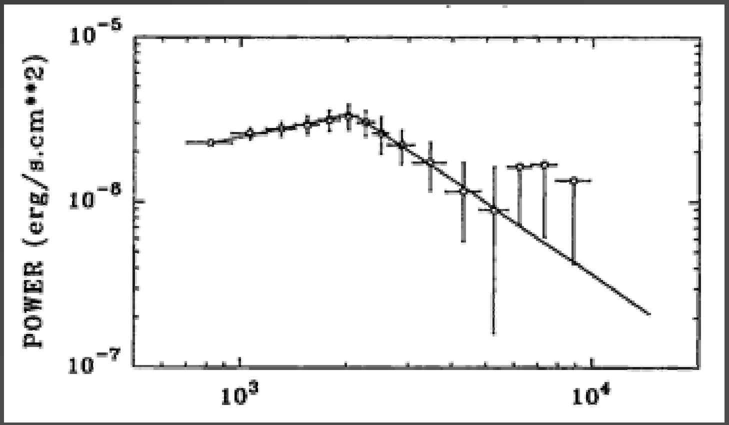
**Observed GRB spectra often agree with theory, but …**

## Broken Power-Law

some spectra have very sharp spectral break




(GRANAT: Pelaez, et al. 1994, ApJ)



# Warning signal #3

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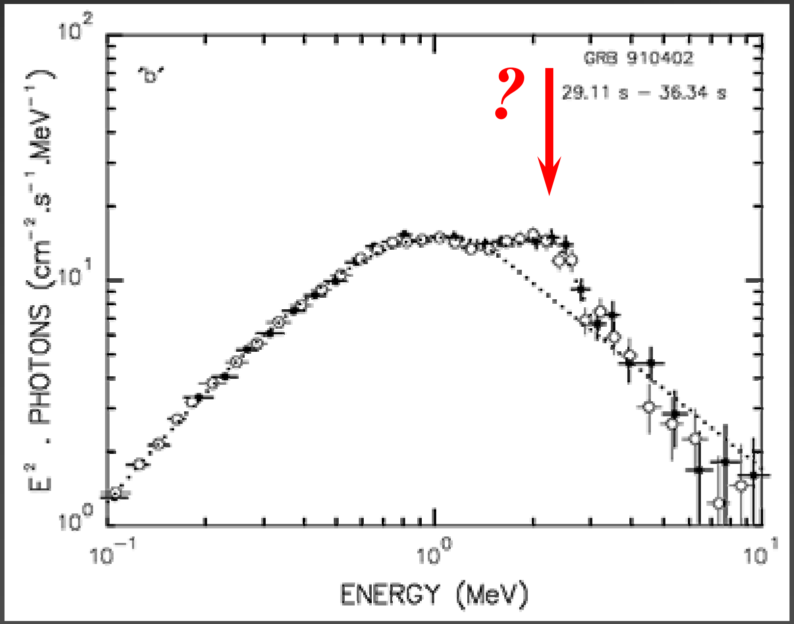



(KONUS: Barat, et al. 2000, ApJ)

**"GRB Lines"**

few spectra exhibit
a spectral feature

# Warning signals #4, #5, …

#4 **Electrons cool fast** → $\alpha < -3/2$

#5 **If break due to cooling** → $\alpha - \beta = 1/2$

#6 **Acceleration of** *e* → **universal** $\beta$

#7 **Why** $\varepsilon_e \sim 1$ **?**

#8 **Why** $\varepsilon_B \sim 1$ **?**

#9 **Collisions are rare** → **what is a** ***shock*** **?**

# What to do?

**~~If you cannot solve a problem --- IGNORE it !~~**

**New physics! (at least for some astronomers)**

*Astrophysical shocks are collisionless,*
*NOT collisional*

# Collisionless Regime

**Particles communicate via Electric and Magnetic fields**

***Plasma:***

- **Nonlinear waves**
- **Turbulence**
- **Wave – particle interaction**
- **Particle kinetics**

**Unlike a hydrodynamic shock,**
**there is *no single theory* of a collisionless shock**

# Shock Zoo

**magnetized**

- *quasi-parallel*
- *quasi-perpendicular*

**unmagnetized**

## Laminar shocks

(nonlinear waves)

- *Alfvenic*
- *ion-acoustic*
- *magnetosonic*

## Turbulent shocks

(effective collisions)

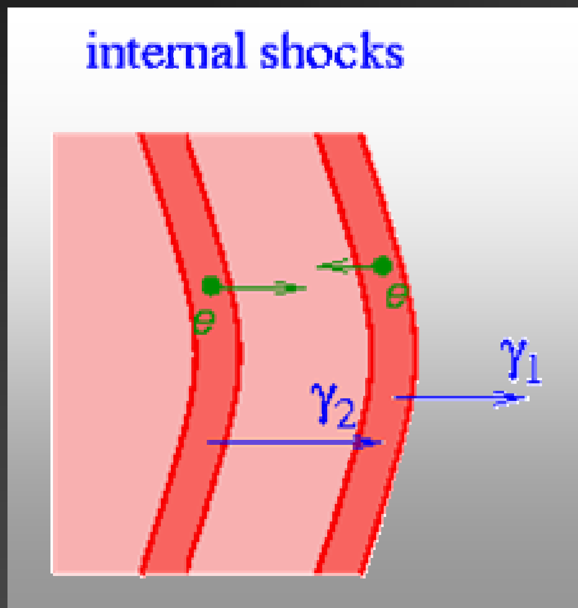
- *ion-acoustic*
- *Langmuir (E-static)*
- *fire hose (magnetic)*
- *two-stream [Weibel] (B-static)*

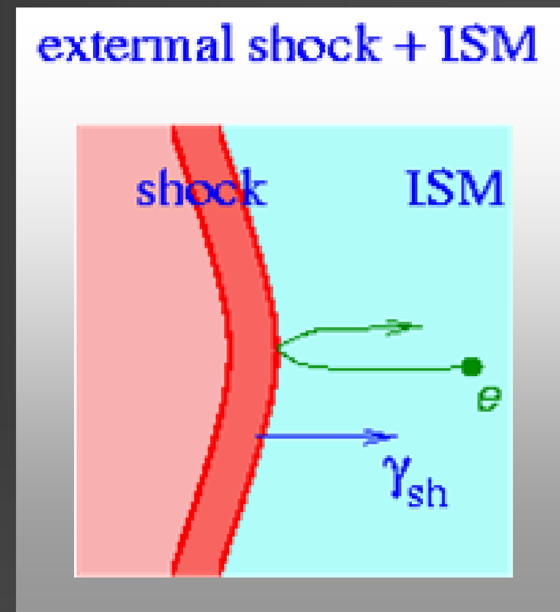
***MHD*** — *Mach* → ***Kinetics***

# Collisionless Shock

***Generation of magnetic fields***

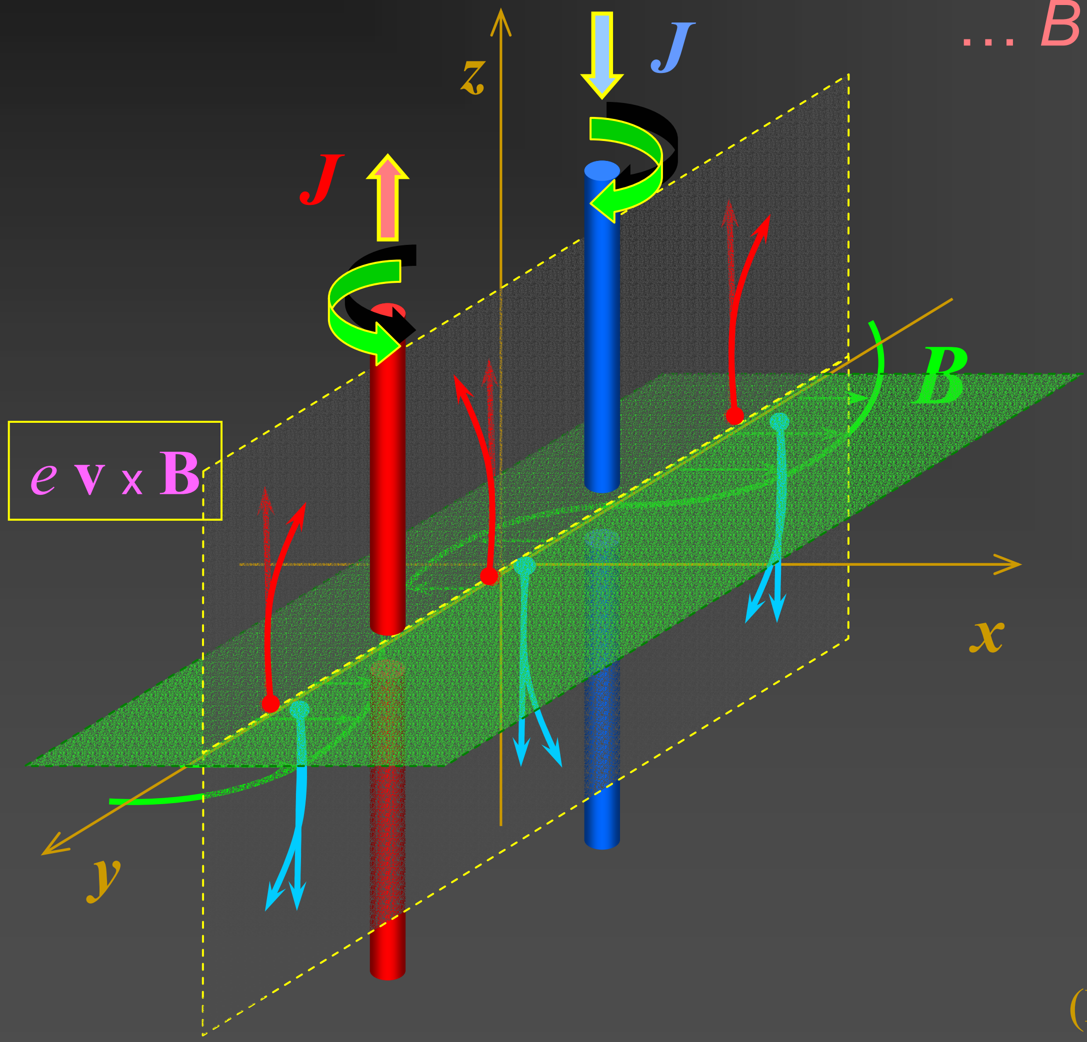
# Zooming-in a Shock




**Electrons and protons form counter-propagating streams in front of the shock - *unstable***

# Weibel (Two-stream) Instability




… current filamentation …
… *B* - field produced …

$\tau = \gamma_{\mathbf{sh}}{}^{1/2} / \omega_{\mathbf{p}}$

$\sim 10^{-8} \ldots 10^{-2}$ s

$\lambda = \gamma_{\mathbf{th}}{}^{1/2}\, \mathbf{c} / \omega_{\mathbf{p}}$

$\sim 10 \ldots 10^{7}$ cm

$\varepsilon_B \sim 0.1$

(Medvedev & Loeb, 1999, ApJ)

# Two-Stream Instability. Theory

- *Kinetic equation:*

$$\partial_t f + \mathbf{v}\cdot\partial_{\mathbf{x}} f + (e/c)\mathbf{v}\times\mathbf{B}\cdot\partial_{\mathbf{p}} f = 0$$

- Distribution function: $f = F(\mathbf{p}) + \tilde{f}$, specify F, $\rightarrow$ Dispersion relation for the *instability*:

$$1 = \frac{c^2k^2}{\omega^2} + \frac{\omega_p^2/\hat{\gamma}}{\omega^2}\left(G(\beta_\perp) + \frac{1}{2}\frac{\beta_\parallel^2}{(1-\beta_\perp^2)}\left|\frac{c^2k^2-\omega^2}{\omega^2-c^2k^2\beta_\perp^2}\right|\right)$$

Here $\beta_\parallel = p_\parallel/\hat{\gamma}mc$, $\beta_\perp = p_\perp/\hat{\gamma}mc$, $\hat{\gamma} = (1-\beta_\parallel^2-\beta_\perp^2)^{-1/2}$, $G(\beta_\perp) = (2\beta_\perp)^{-1}\ln[(1+\beta_\perp)/(1-\beta_\perp)]$, and $p_\parallel$ and $p_\perp$ are averaged particle momenta *(Yoon & Davidson 1987, Phys. Rev. A, 35, 2718)*

- Instability occures for $k$:

$$0 < k^2 < k_{crit}^2 \equiv \left(\frac{\omega_p^2}{\hat{\gamma}c^2}\right)\left|\frac{\beta_\parallel^2}{2\beta_\perp^2(1-\beta_\perp^2)} - G(\beta_\perp)\right|$$

- Most unstable mode for $\gamma_\parallel \gg \gamma_\perp \gg 1$:

$$\Gamma_{max}^2 \simeq \frac{\omega_p^2}{\gamma}\left(1-2\sqrt{2}\frac{\gamma_\perp}{\gamma}\right), \qquad k_{max}^2 \simeq \frac{1}{\sqrt{2}}\frac{\omega_p^2}{\gamma_\perp c^2}\left(1-\frac{3}{\sqrt{2}}\frac{\gamma_\perp}{\gamma}\right)$$

- Saturation:

$$k_{max}\rho \sim 1 \;\Rightarrow\; \epsilon_B = \frac{B^2/8\pi}{mc^2 n(\bar{\gamma}-1)} \sim \frac{(\bar{\gamma}+1)}{2\sqrt{2}\,\bar{\gamma}} \qquad \text{simulations :} \quad \begin{array}{l}\epsilon_{Bp} \sim \eta_p \sim 0.1-0.01\\ \epsilon_{Be} \sim (m_e/m_p)\eta_e \sim 10^{-4}\end{array}$$

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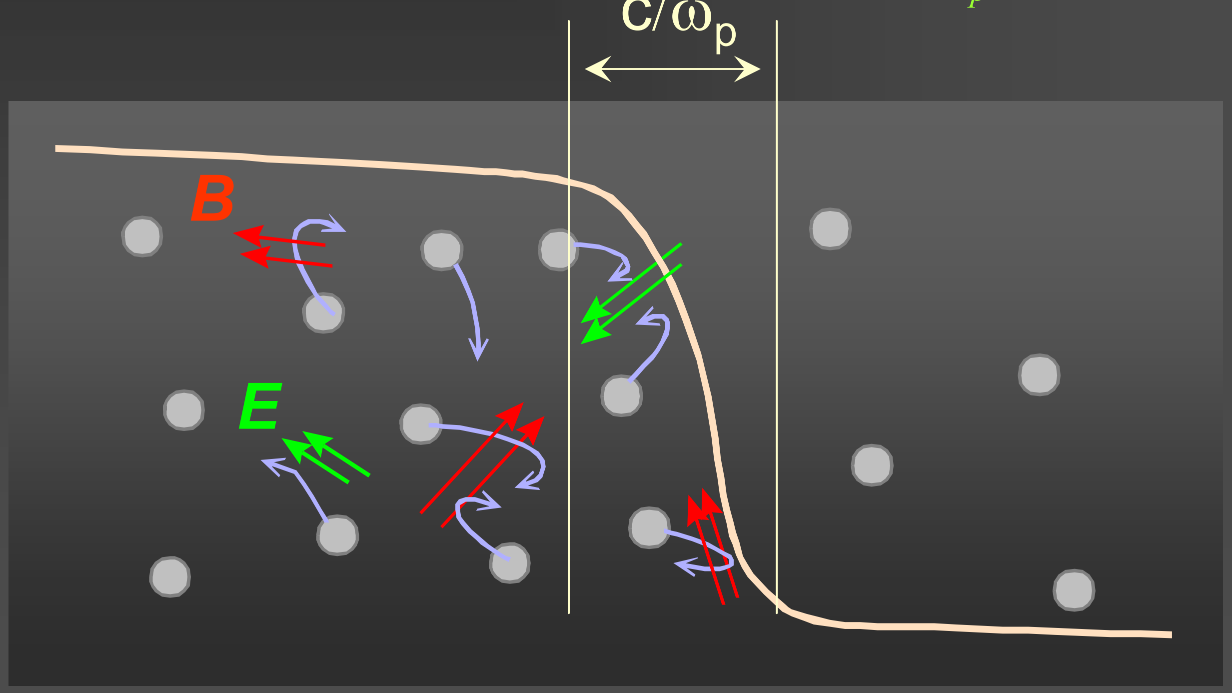
# Turbulent Collisionless Shock

**Electric and/or magnetic fields are needed to randomize particles**

$$\omega_p = \sqrt{4\pi e^2 n / m}$$

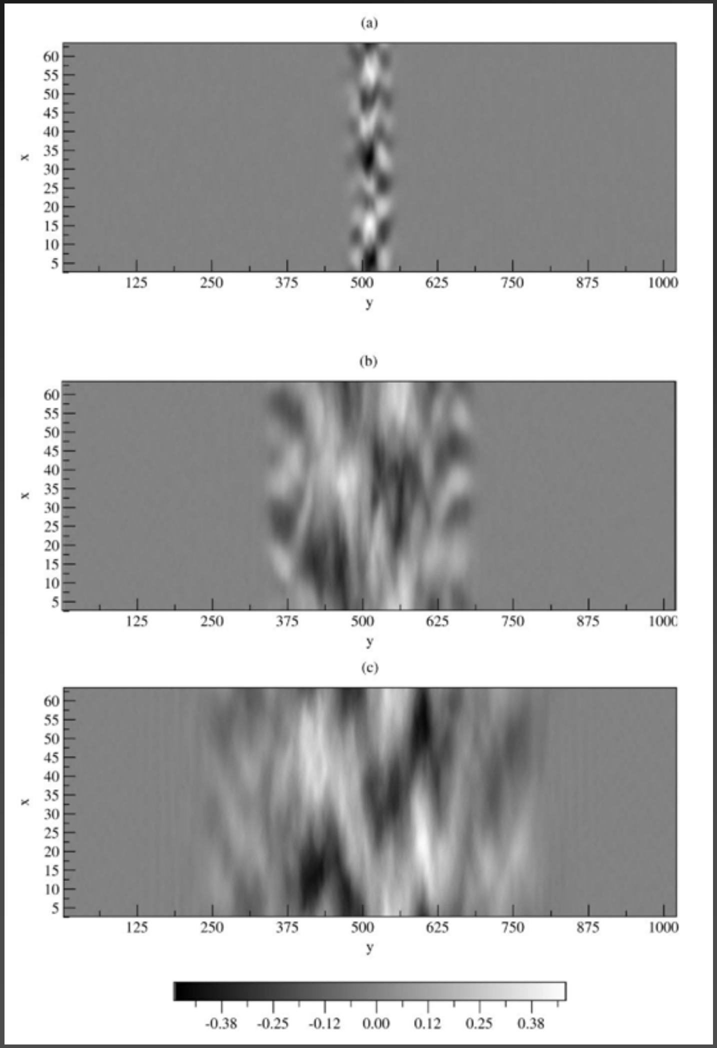


# Simulations

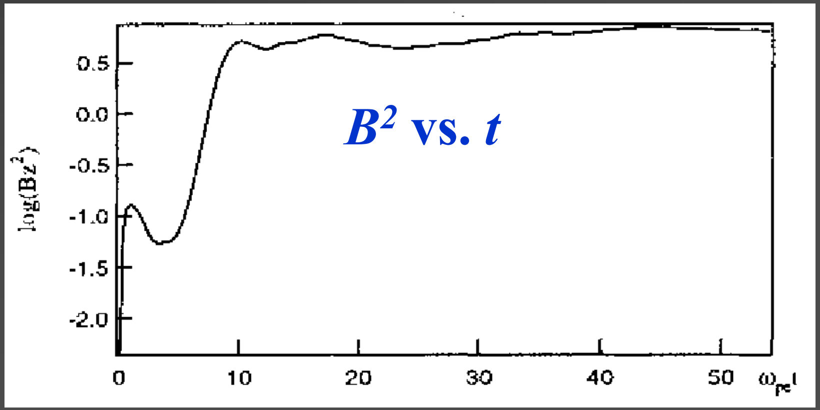
- *USA/Portugal (2D & 3D !!!)*
  - Silva, Fonseca, Mori, et al. … 2000-…

- *Japan (2D)*
  - Kazimura, Sakai, & Bulanov … 1998-…
- *Italy (2D)*
  - Califano, Pegoraro, Bulanov, et al. … 1998
- *USA*
  - Yang, Arons, & Langdon … 1994
  - Gruzinov (same code as Kazimura et al.) … 2001

# *B*-field Structure

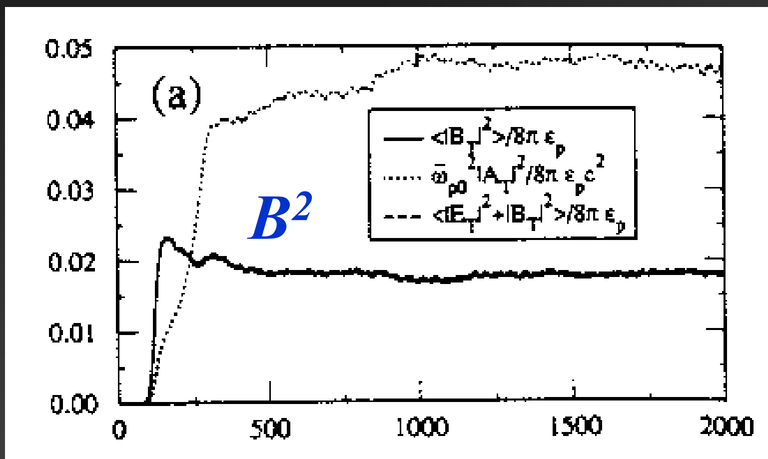



**Field grows on small (skin-depth) scales**



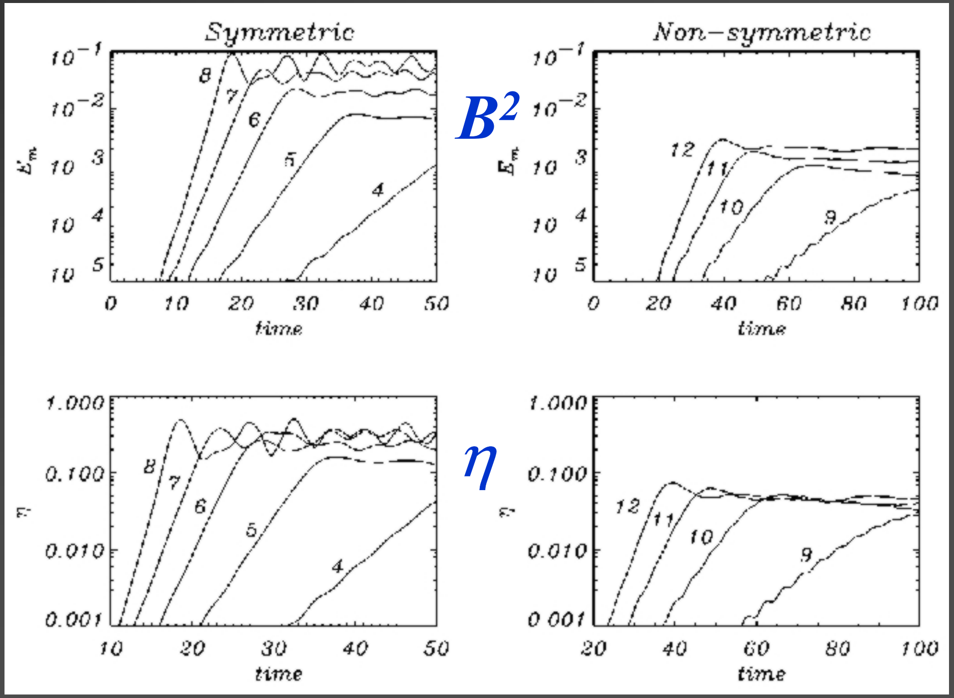

(Kazimura, et al. 1998, ApJL)

# Energy, Efficiency, …




(Yang, Arons, Langdon 1994)

**B-field does <u>not</u> dissipate**



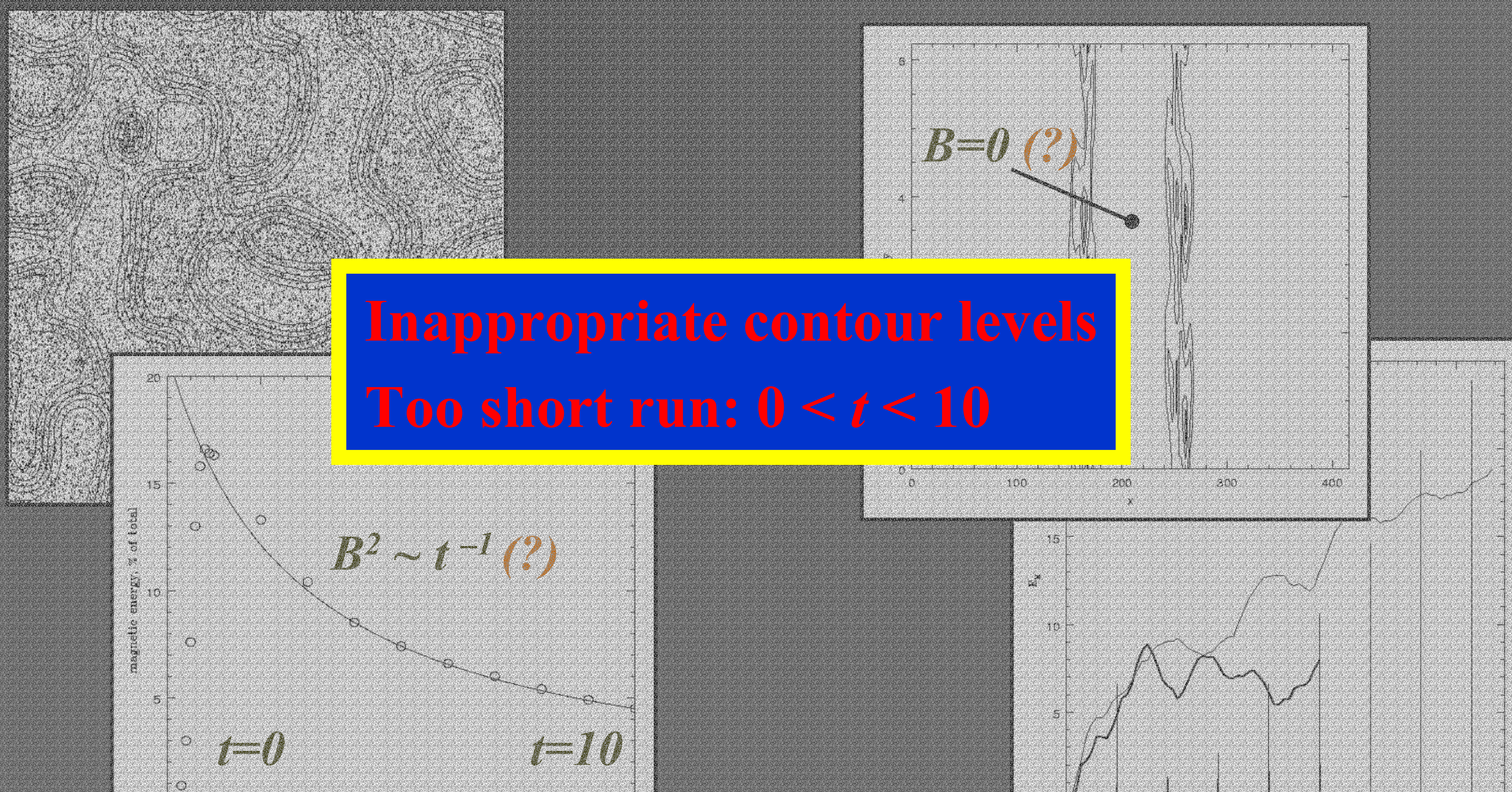

(Califano, et al. 1998, PRE)

**Efficiency is high:**

**η = few %**

# A Conflict ?

**Some 2D simulations seem to show field decay ???**




(Gruzinov 2001)

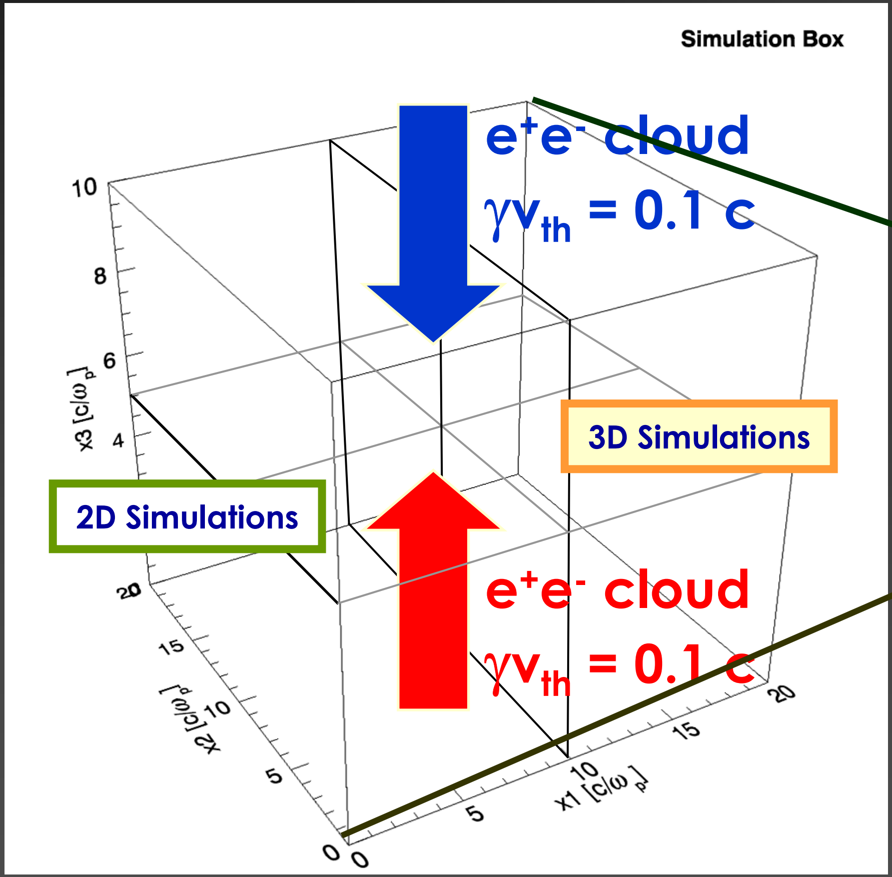
# Fully 3D PIC $e^{-}e^{+}$ Simulations

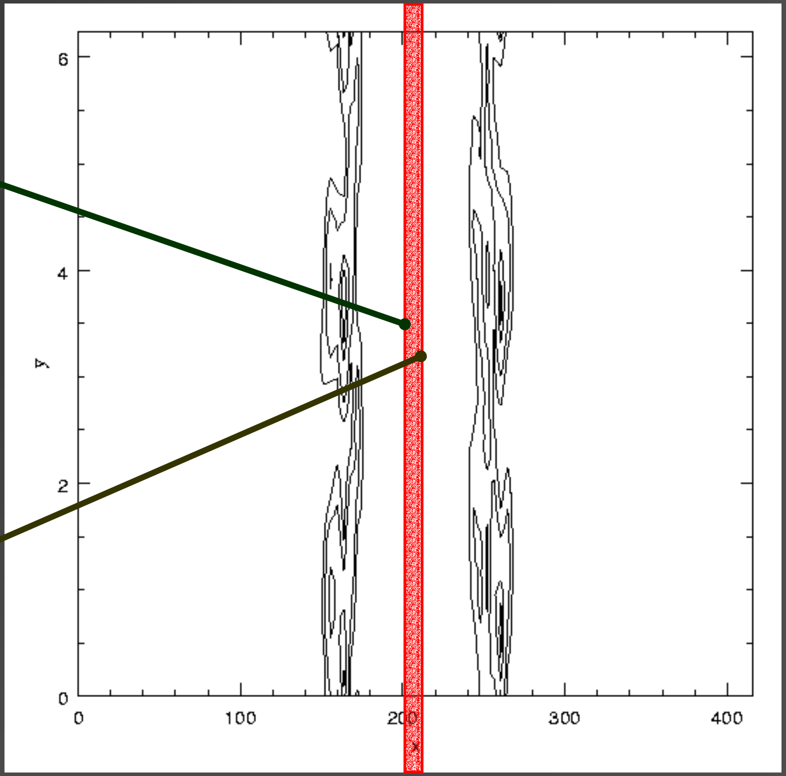
**R. Fonseca, J. Tonge, R.G. Hemker, L.O. Silva, J.M. Dawson, W.B. Mori, M.V. Medvedev**

## OSIRIS Code

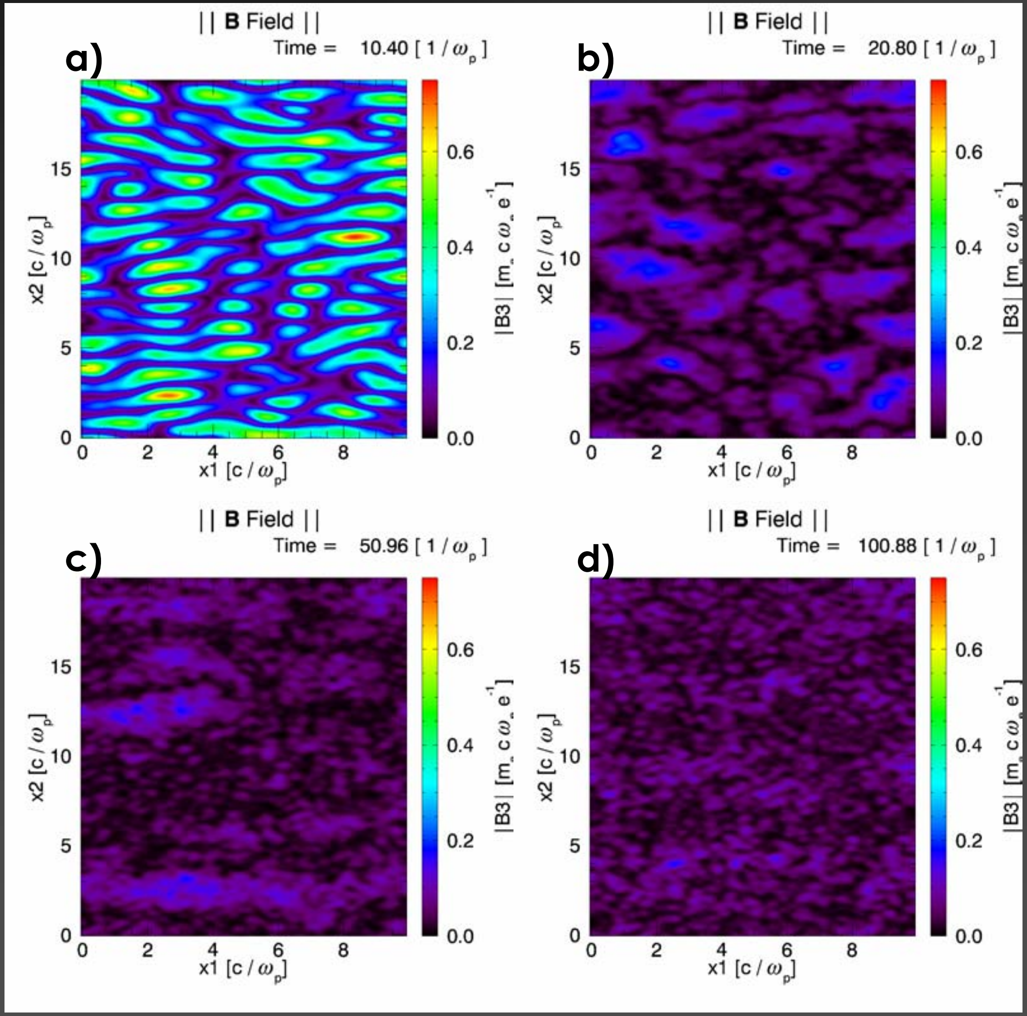
- Massively parallel, 3D, PIC code
- Fully object oriented code design
- Fully parallel multi-platform implementation

# Simulation Parameters

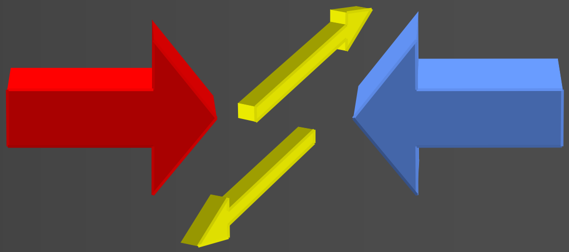


# 2D Edge-on: Magnetic Field




$\gamma v = 0.6\ c$



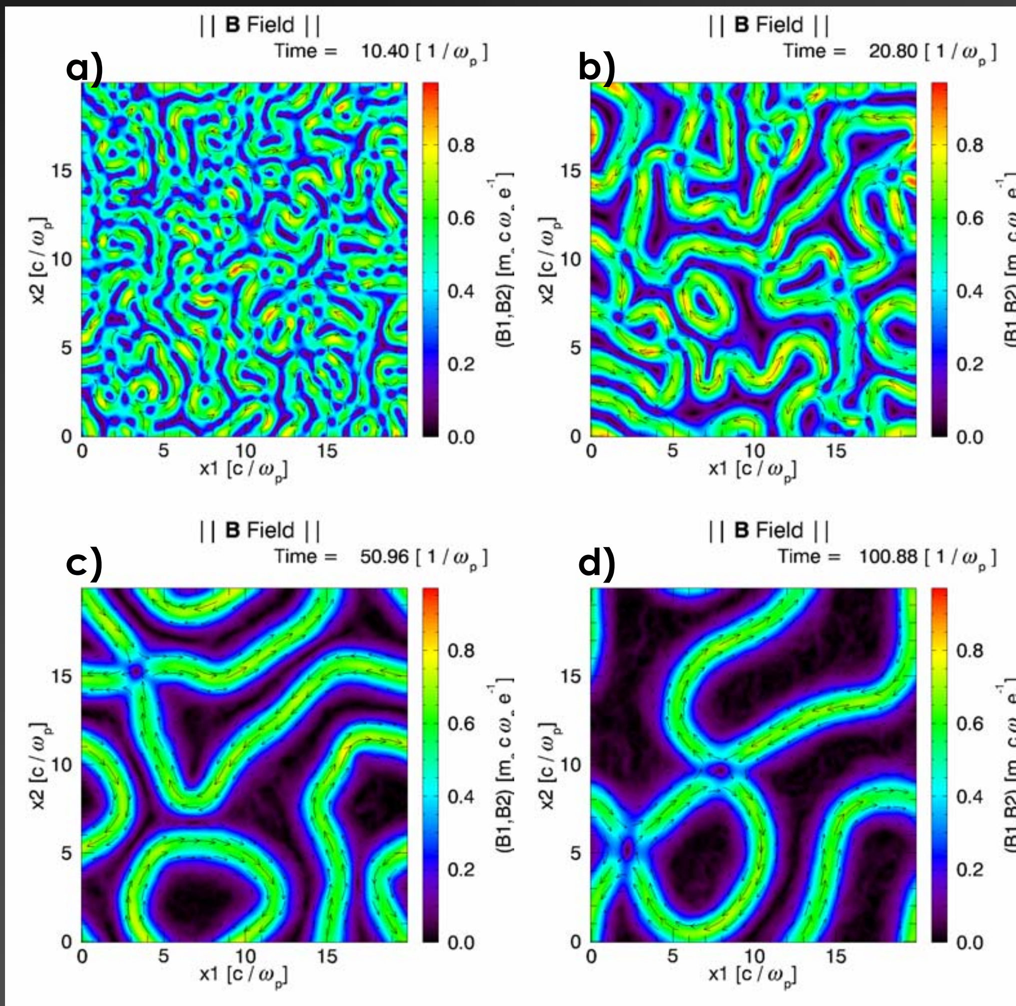
a) $t = 10.1\ \omega_p^{-1}$,

b) $t = 20.8\ \omega_p^{-1}$,

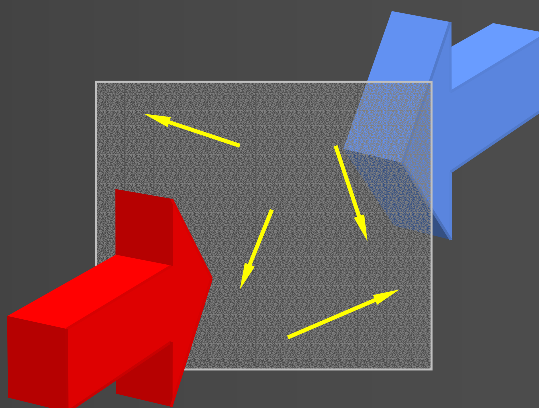
c) $t = 50.96\ \omega_p^{-1}$,

d) $t = 100.88\ \omega_p^{-1}$

# 2D Face-on: Magnetic Field




$\gamma v = 0.6$ c



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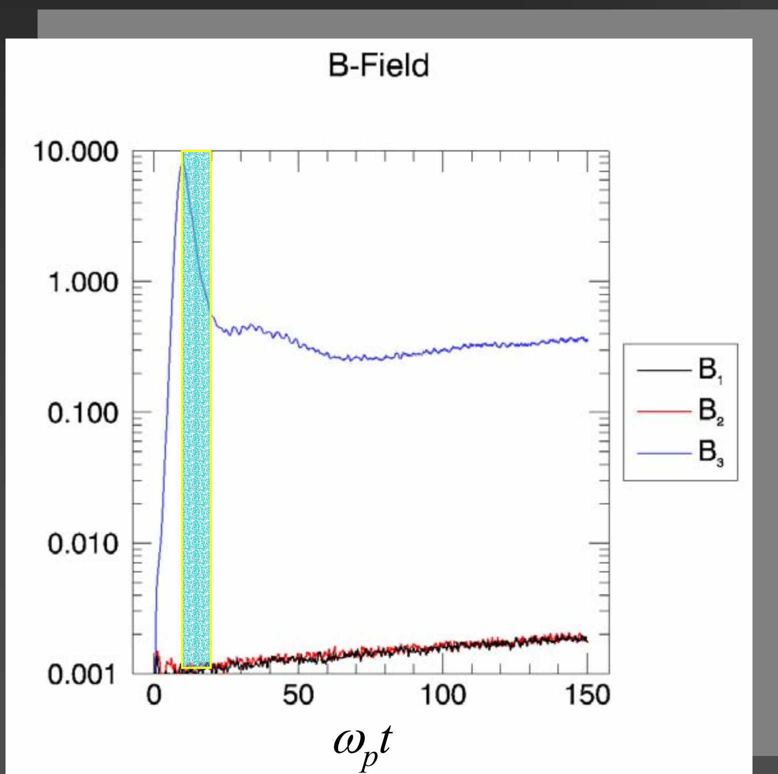
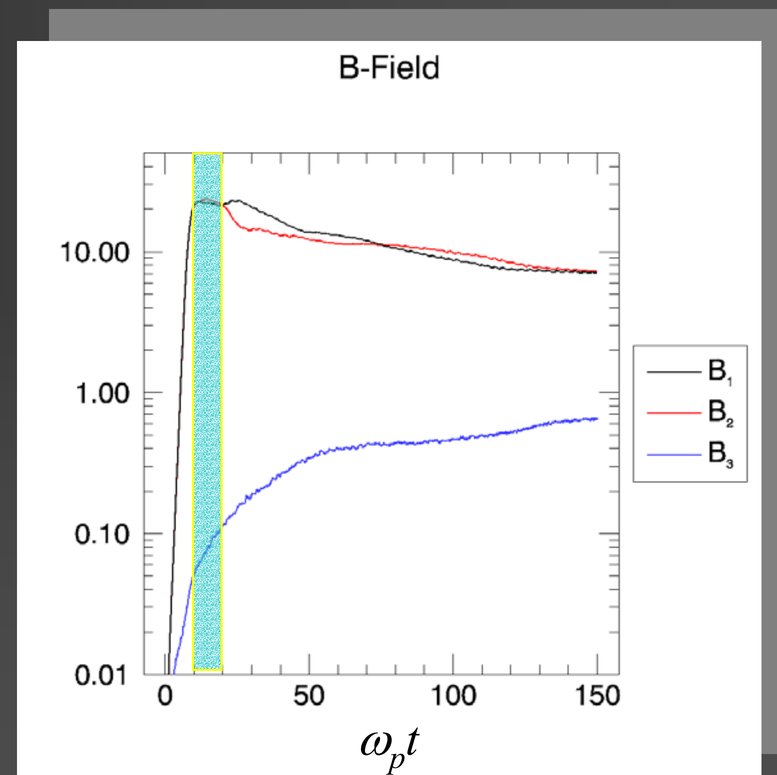
# 2D Magnetic Field Strength

$\gamma v = 0.6\ c$

**Edge-on**



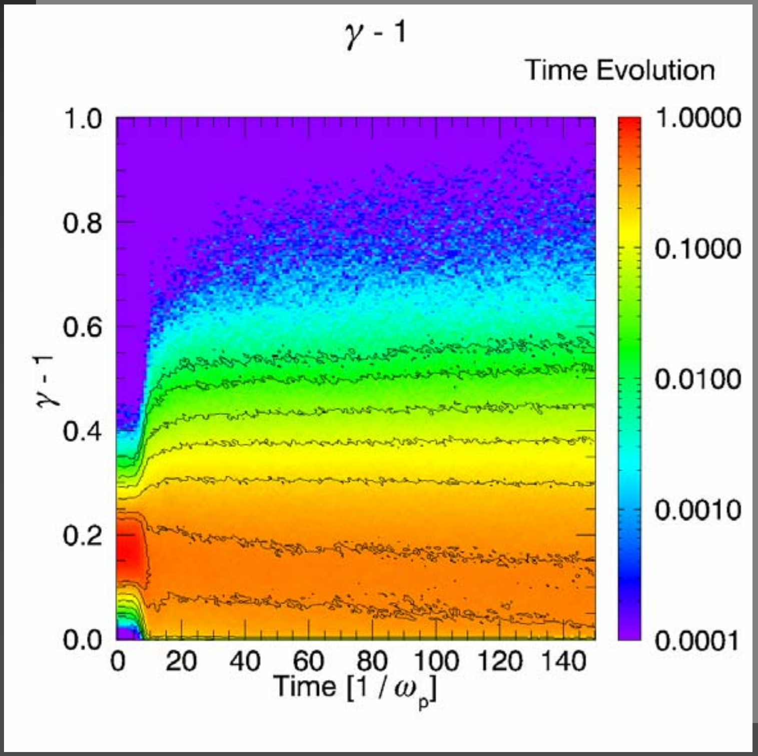

**Face-on**



# 2D Particle Distribution

$\gamma v = 0.6\ c$

**Edge-on**

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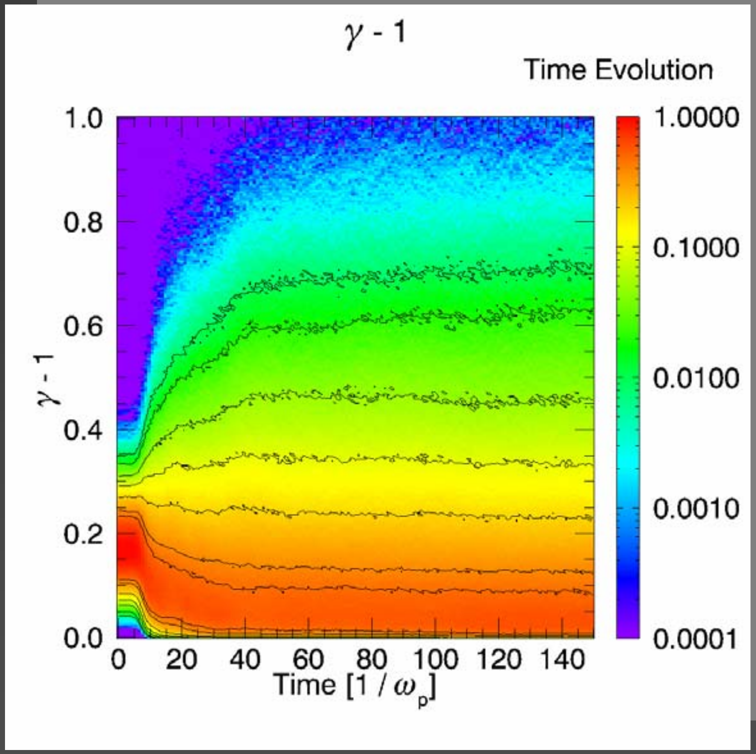

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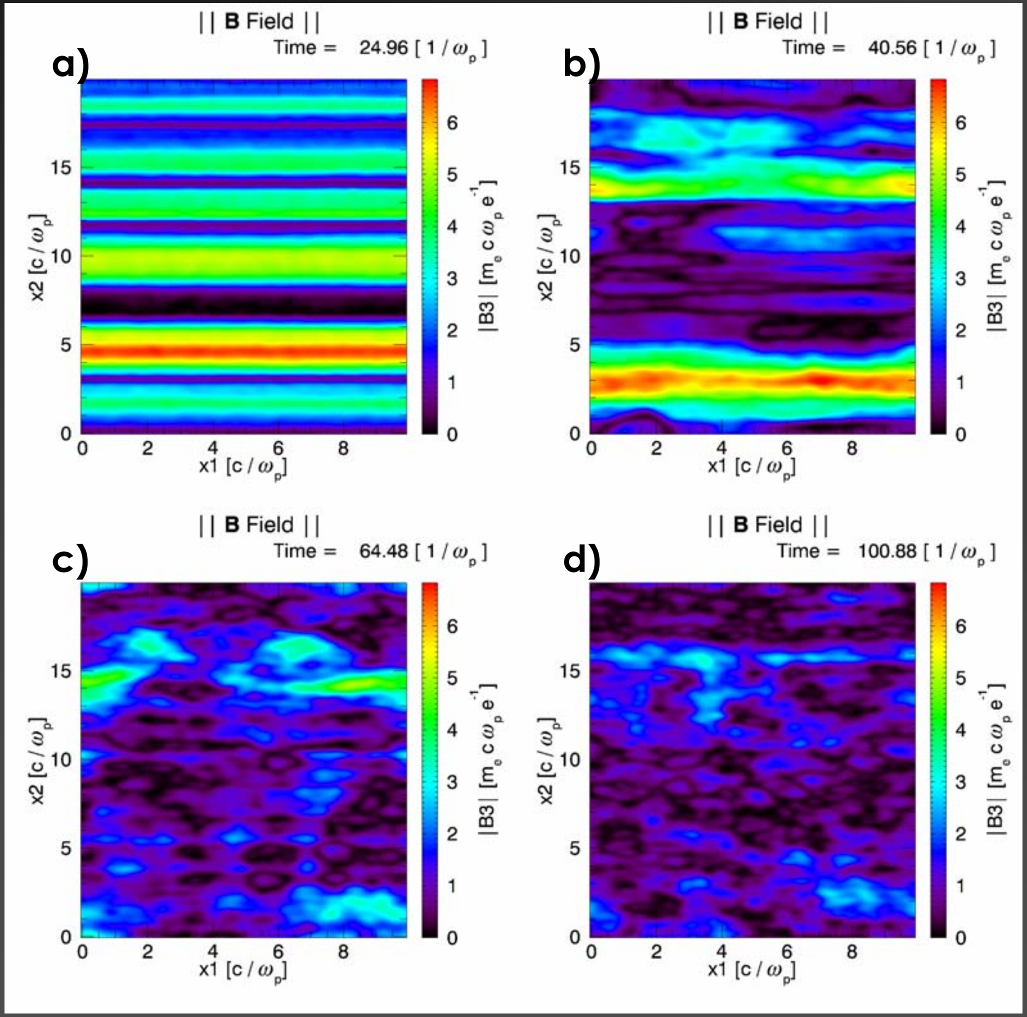
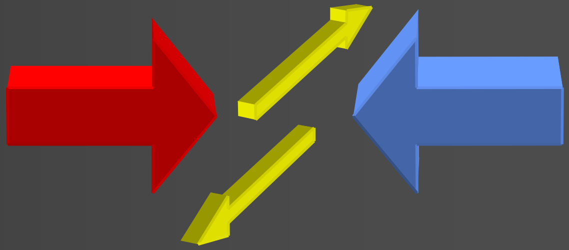



$\gamma v = 10\ c$



a) $t = 24.96\ \omega_p^{-1}$,

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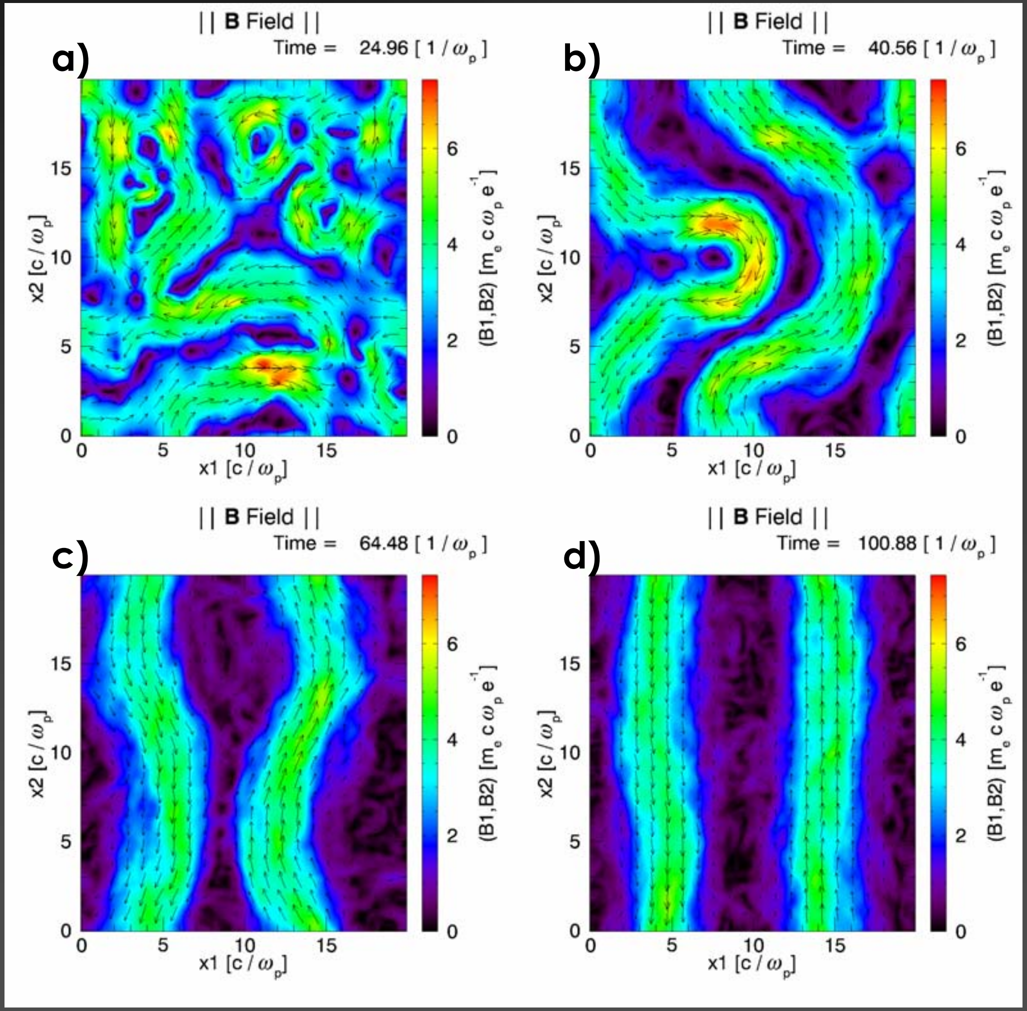
# 2D Face-on: Magnetic Field

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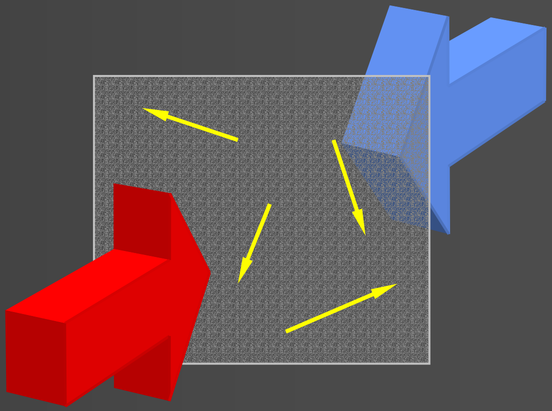

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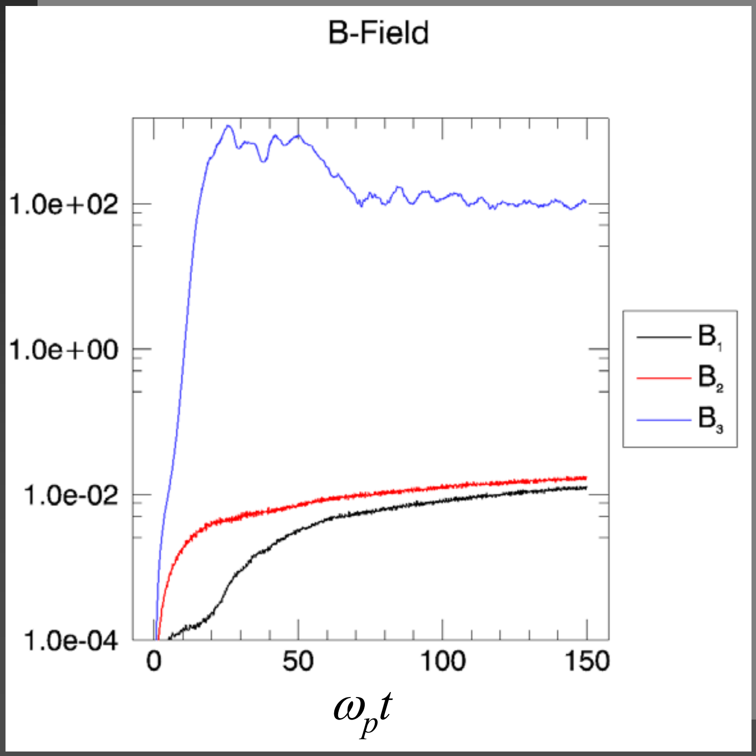
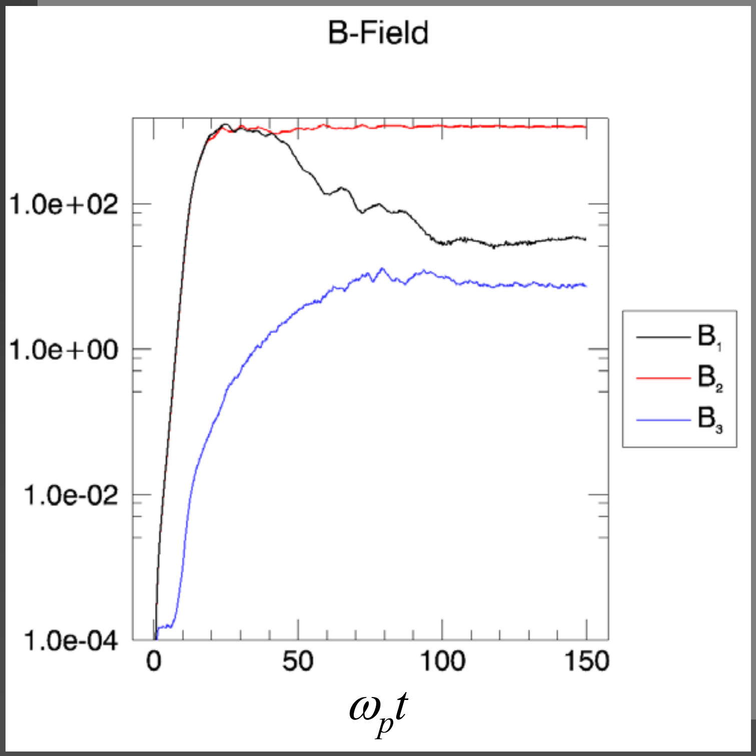
# 2D Magnetic Field Strength

$\gamma v = 10$ c

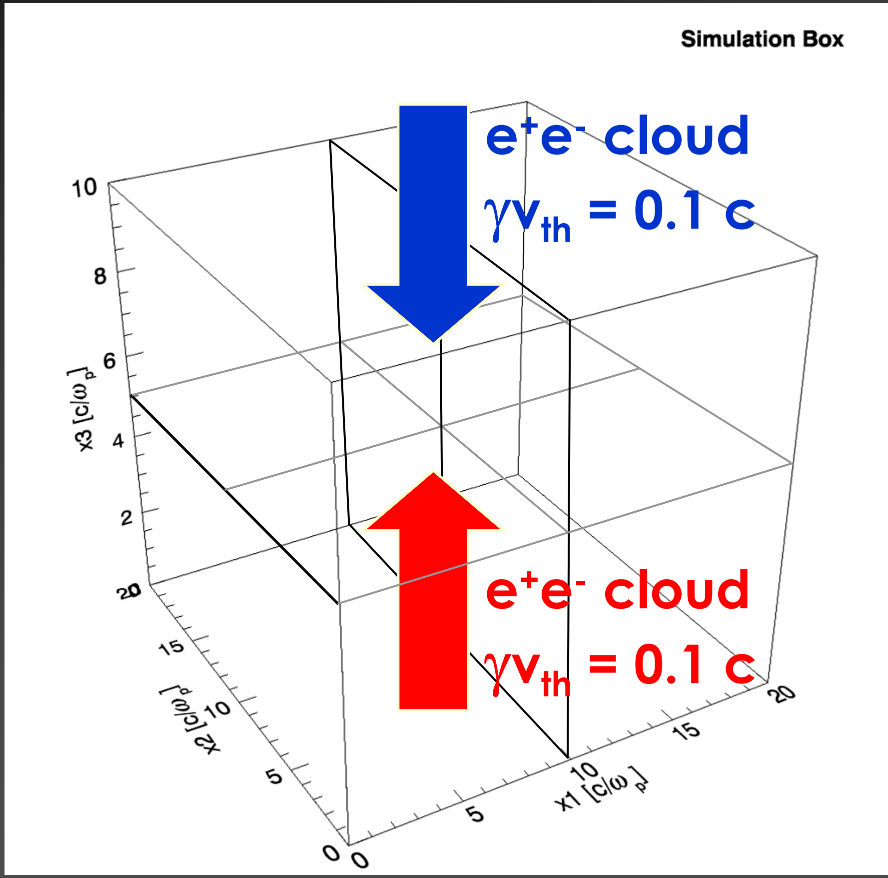
## Edge-on




## Face-on

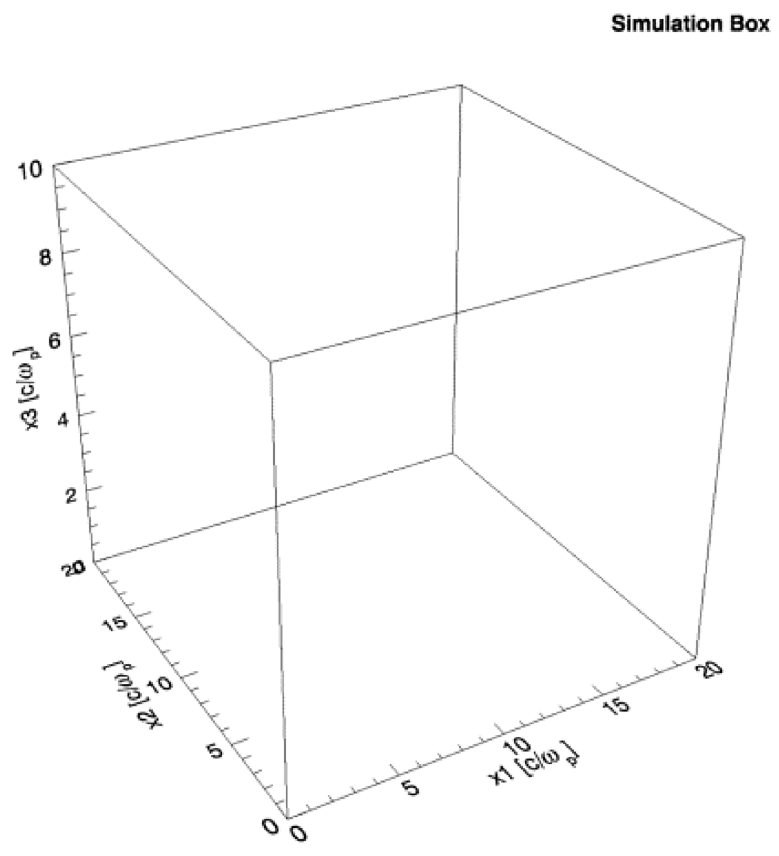


# 3D Simulation Parameters




- **3D Simulation**
  **105 Million** particles
  256 x 256 x 100 cells
  (25.6 x 25.6 x 10 $c^3/\omega_p{}^3$ volume)
  (6 particles/species/cell)
  $\gamma v$ = 0.6 c, 10 c

# Current Filamentation




**$\gamma v = 0.6\ c$**

**<u>Iso-surfaces:</u>**

**RED - positive $J_z$**

**BLUE - negative $J_z$**

Contours are at $n = 1.1\ n_0$

a) $t = 10.1\ \omega_p^{-1}$,

b) $t = 20.8\ \omega_p^{-1}$,

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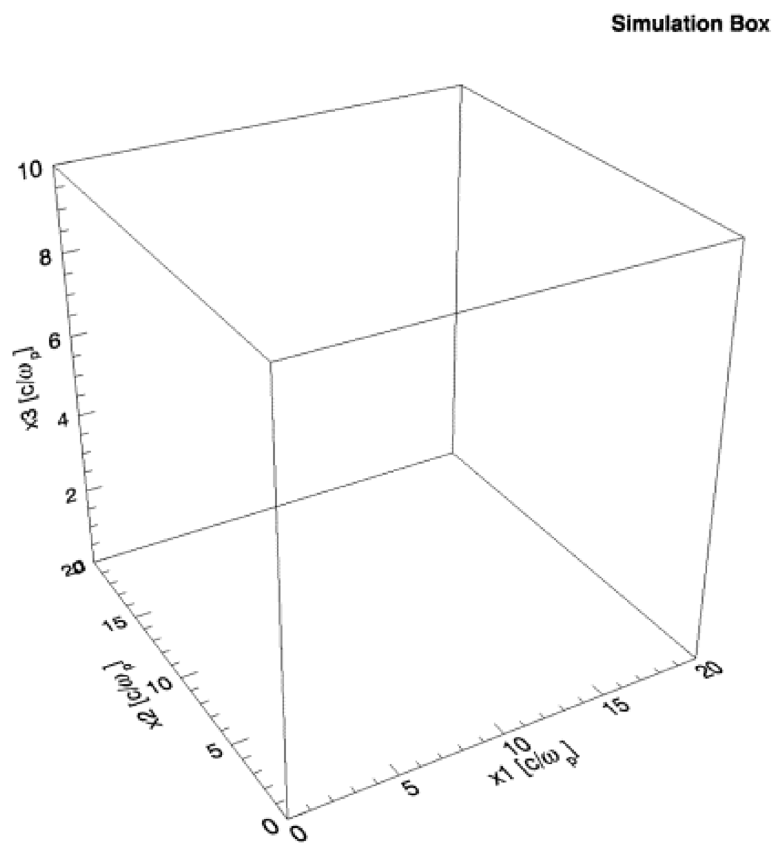
# Magnetic Filaments




**$\gamma v = 0.6$ c**

**Iso-surfaces:**

**From RED to GREEN :**

0.1 - 0.025 - 0.01 - 0.006

a) $t = 10.1\ \omega_p^{-1}$,

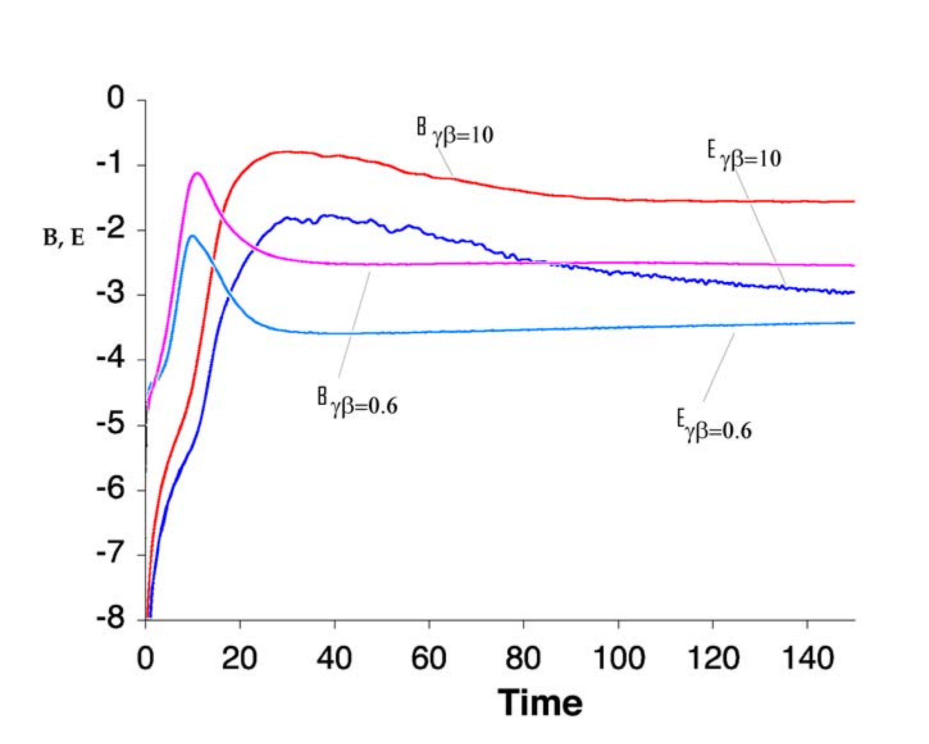
b) $t = 20.8\ \omega_p^{-1}$,

c) $t = 50.96\ \omega_p^{-1}$,

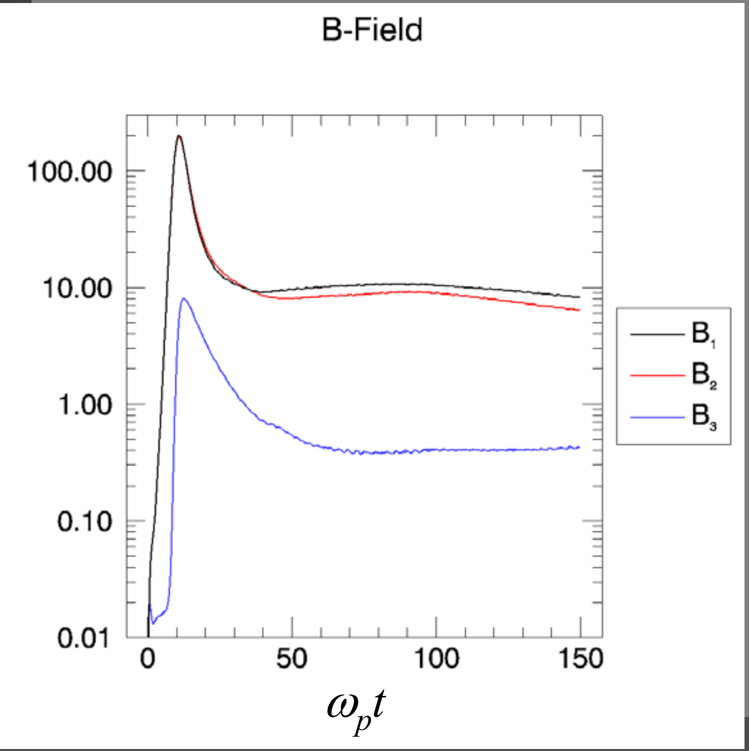
d) $t = 100.88\ \omega_p^{-1}$

# Field Strength

## Log( $B^2, E^2/8\pi$ $E_{kin}$ )

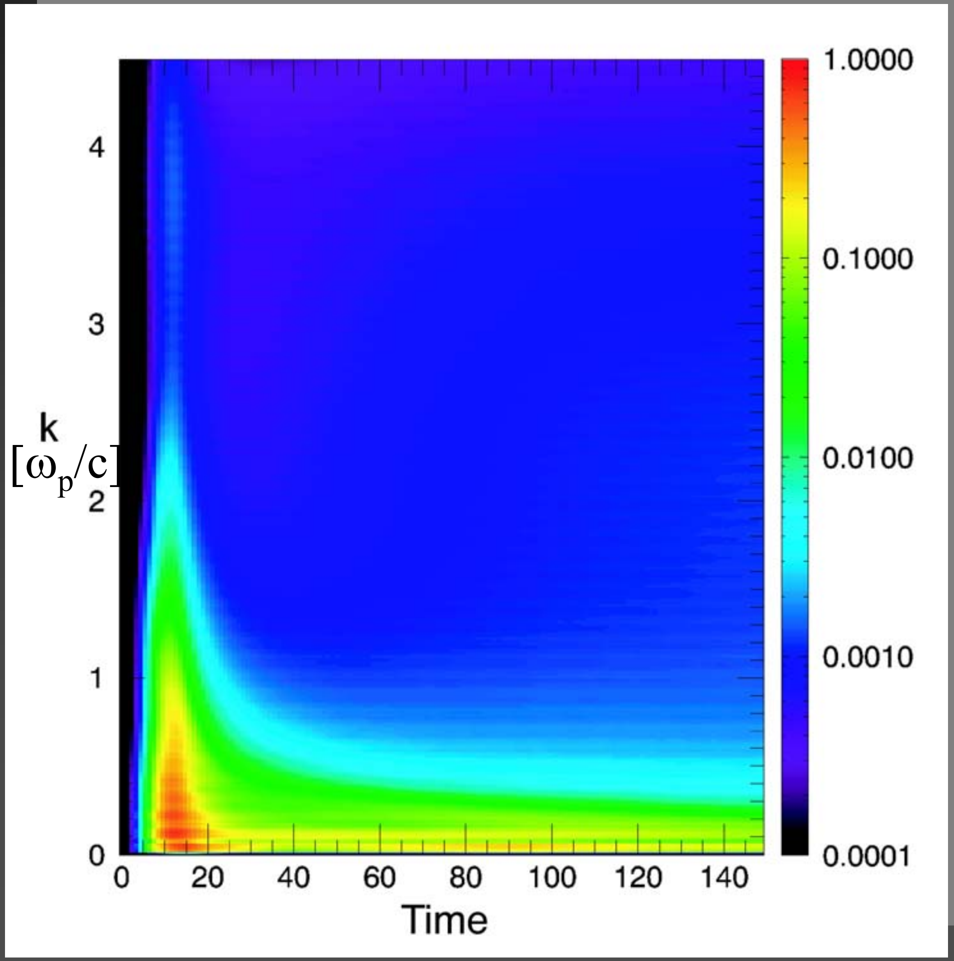



## Field components



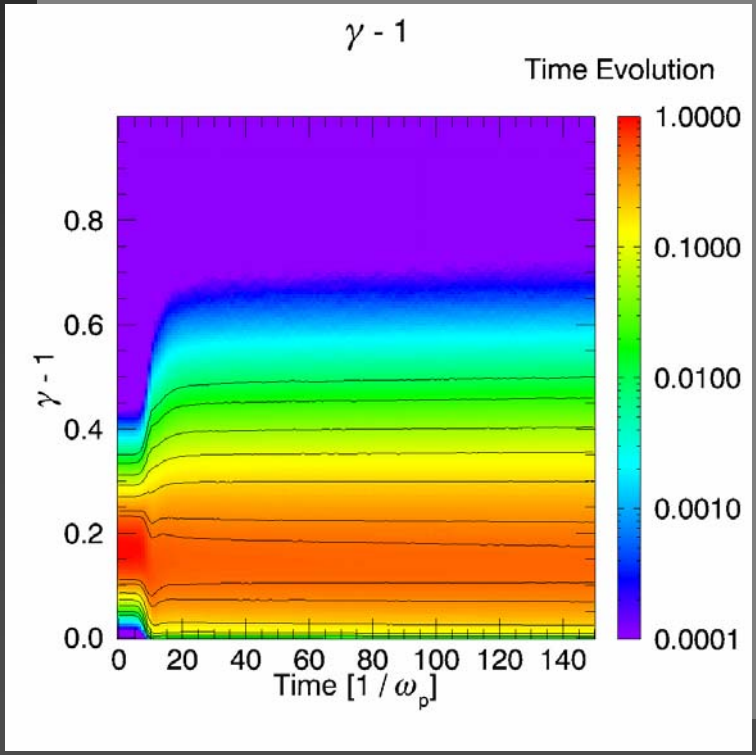
# 3D Field Spectrum

$\gamma v = 10\ c$

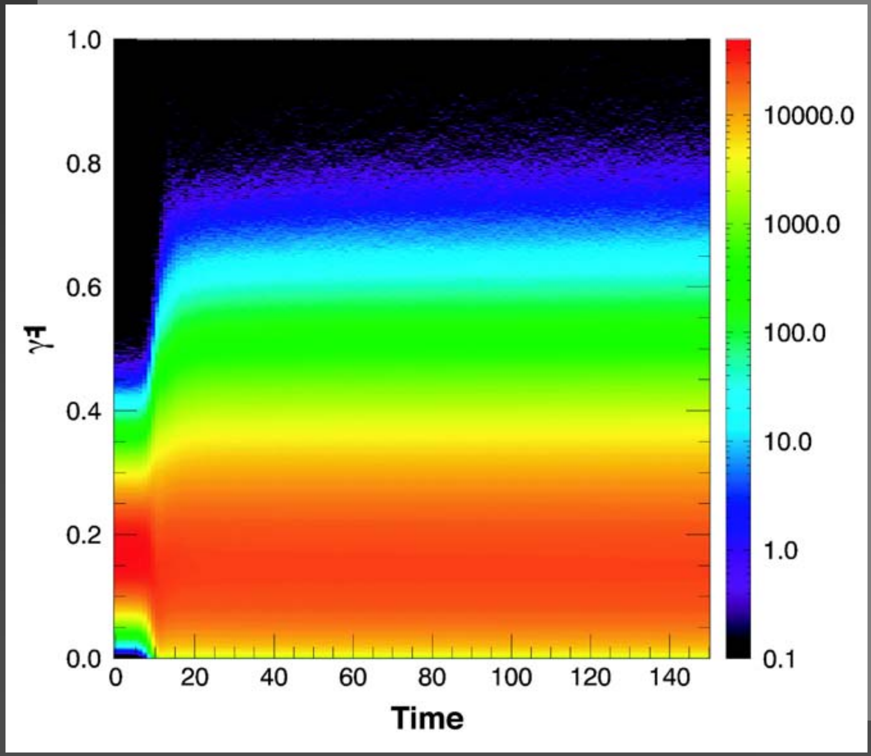


# 3D Particle Distribution

$\gamma v = 0.6\ c$




$\gamma v = 10\ c$



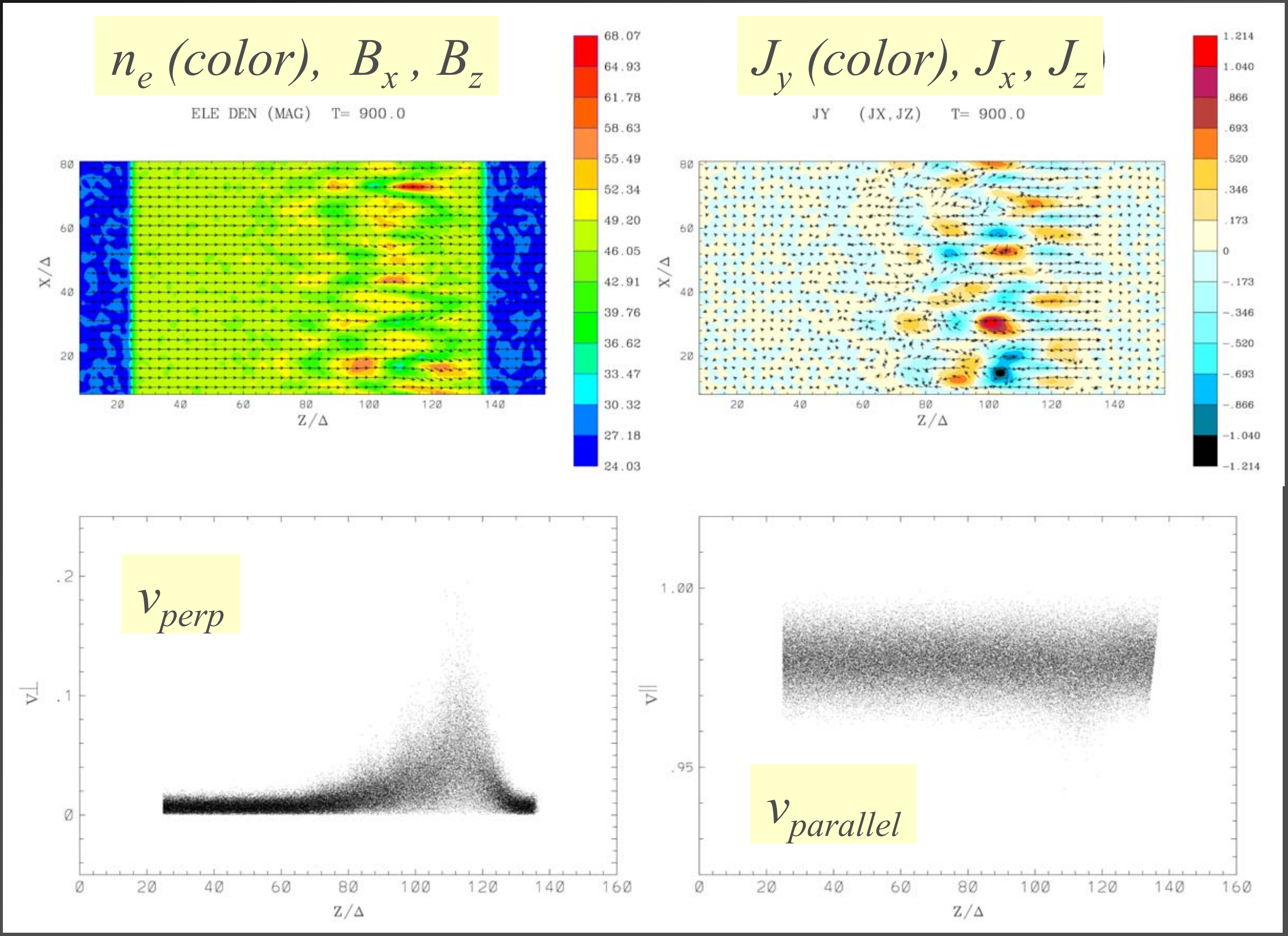
# Fully 3D PIC *$e^-$-"ion"* Simulations

**K.-I. Nishikawa, P. Hardee, G. Richardson, R. Preece, H. Sol, G. J. Fishman**

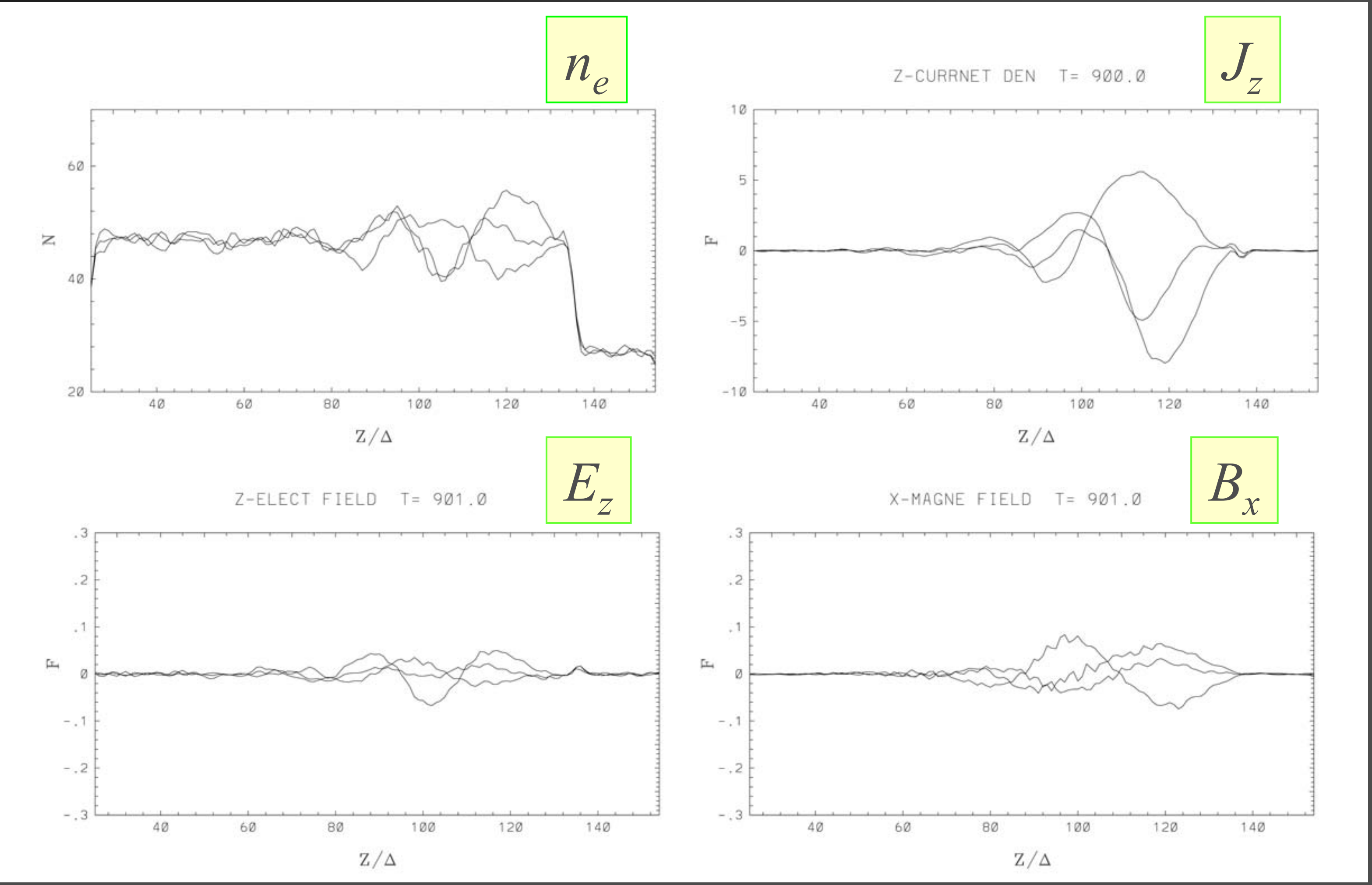
# Modified TRISTAN Code

- Relativistic, electromagnetic, 3D, PIC code
- $m_i/m_e=20$
- 85x85x160 grid, 85 million particles
- $n_{inj}=0.7n_0$, $\gamma_{inj}=5$, $v_{th}=0.1v_{inj}$, $M_A=12.7$

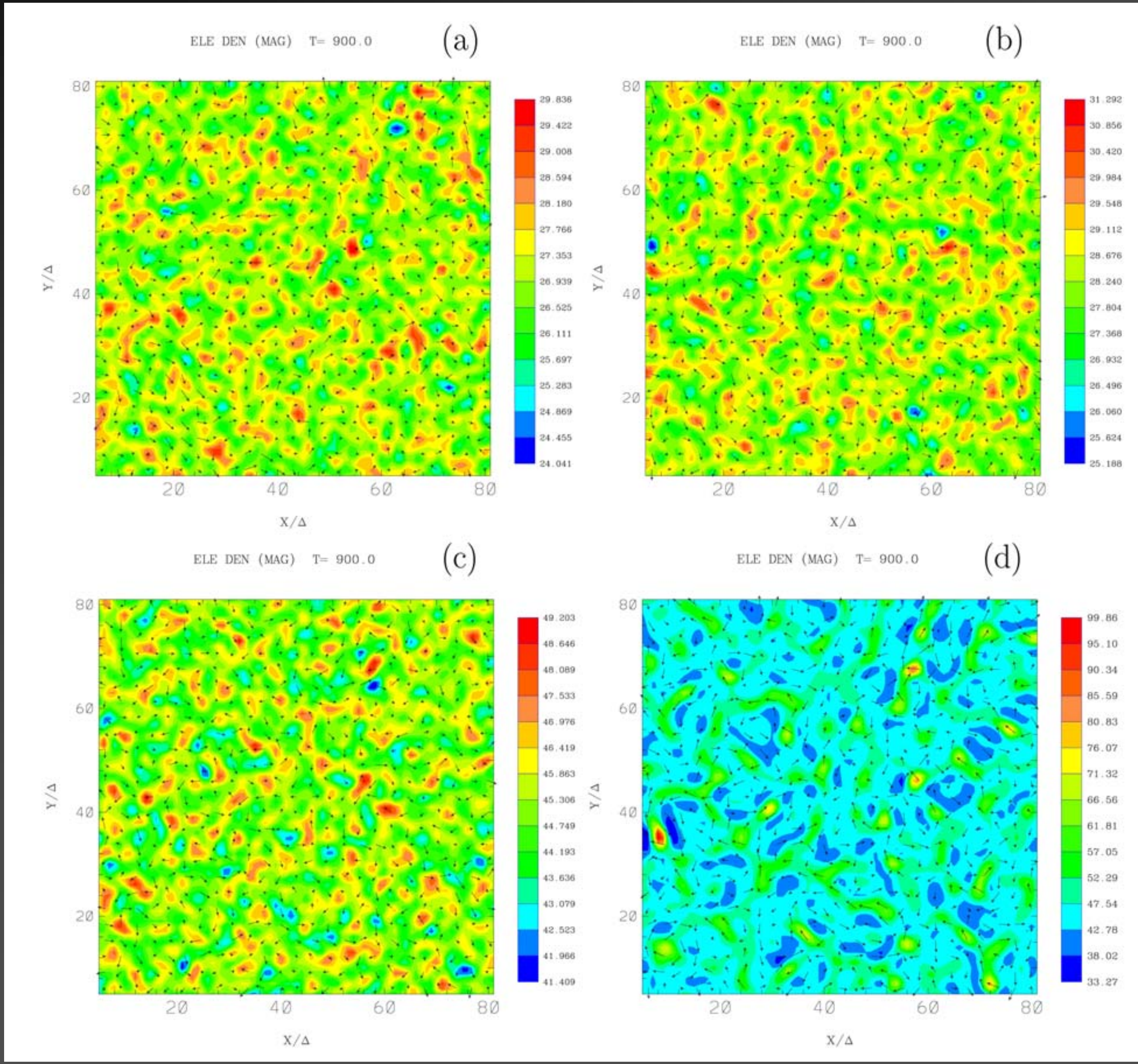
# Formation of a shock



# Formation of a shock *(cont.)*



# Shock head: face-on slices




$n_e$, $(B_x, B_y)$

*at*

$Z/\Delta = 140$

137

134

120

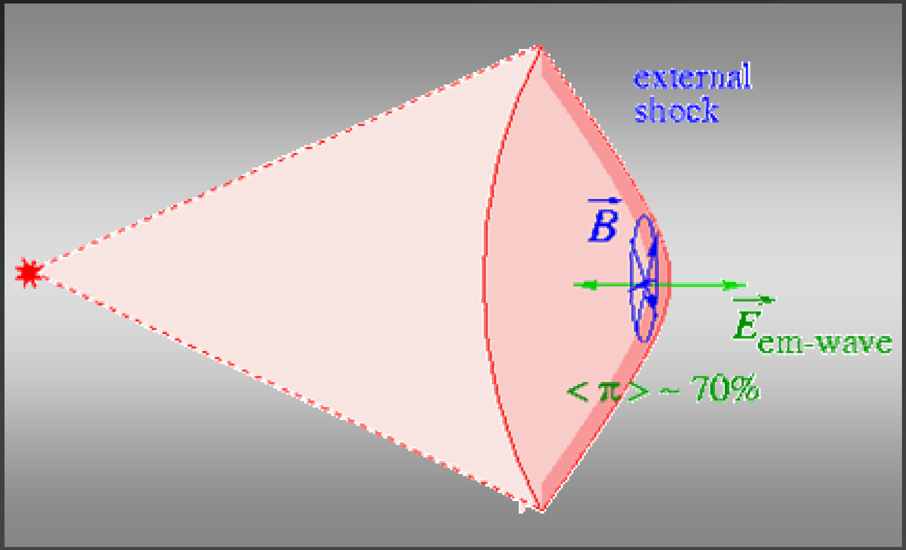
# Summary on Magnetic Field

- **Magnetic field is produced**
- **Field geometry**
  - *Random, but mostly in the plane of a shock*
  - *Small-scale, compared to dynamical*
  - *Evolves to larger scales*
- **Field strength**
  - *Sub-equpartition, $\varepsilon_B < 0.1$*
  - *Evolves to & saturates at $\varepsilon_B = 10^{-3} \ldots 10^{-4}$*
- **No decay on plasma time-scale**

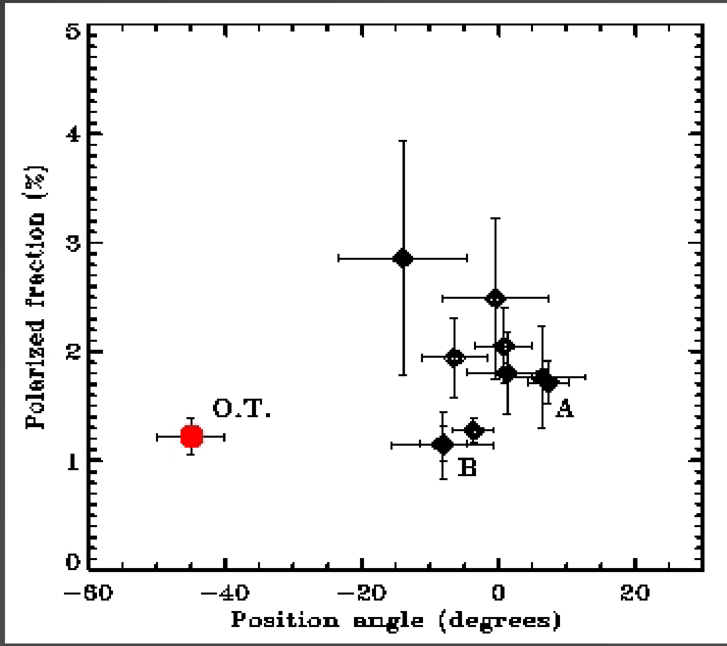
# Observational Predictions

- **Polarization of beamed afterglows**
- **Scintillations of polarization of radio afterglows**
- **Novel emission mechanism :**
  ***Jitter radiation***

# Polarization of Afterglows




**Beamed ejecta (jet)**

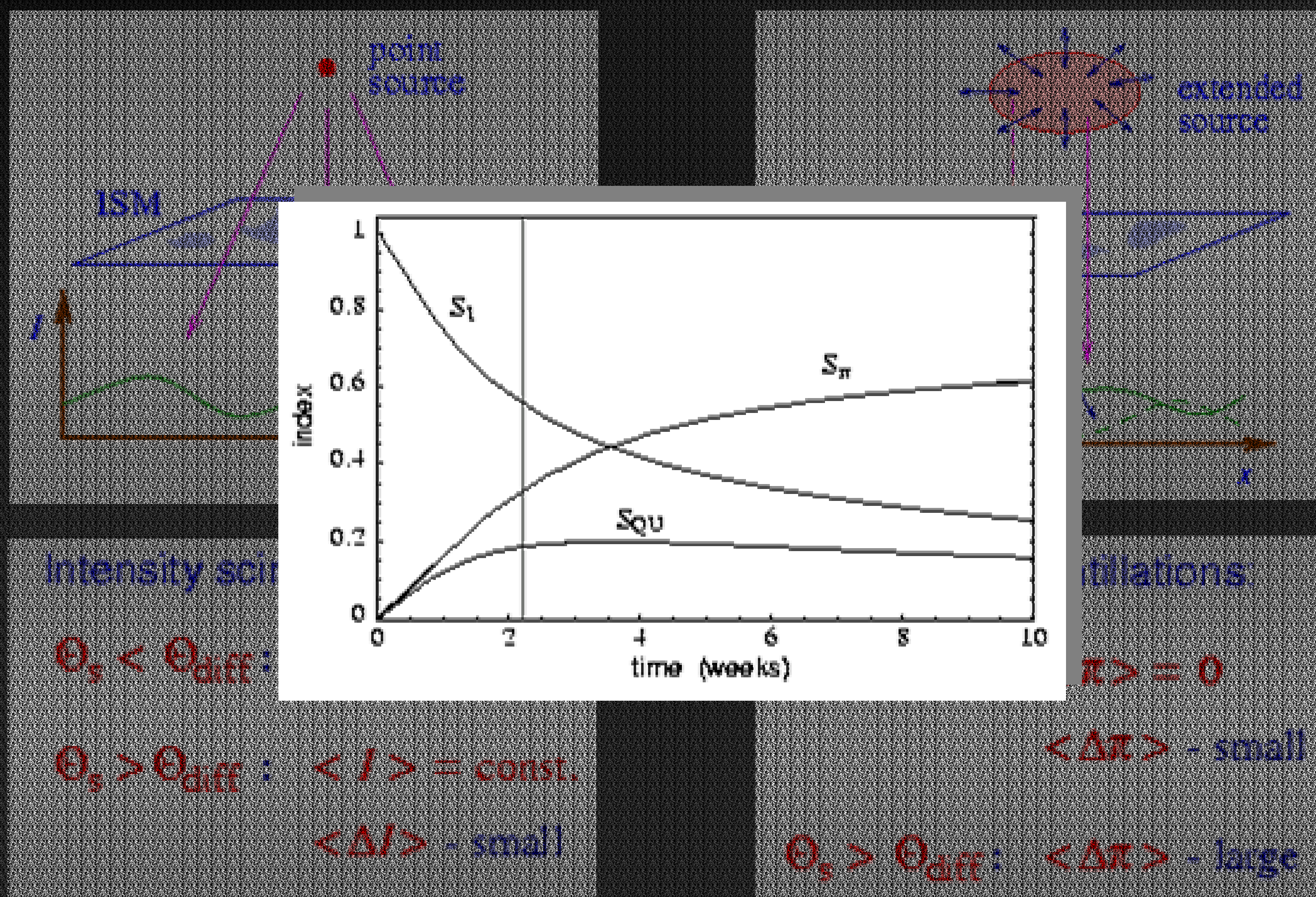



**GRB 990510**

**polarization of optical transient**

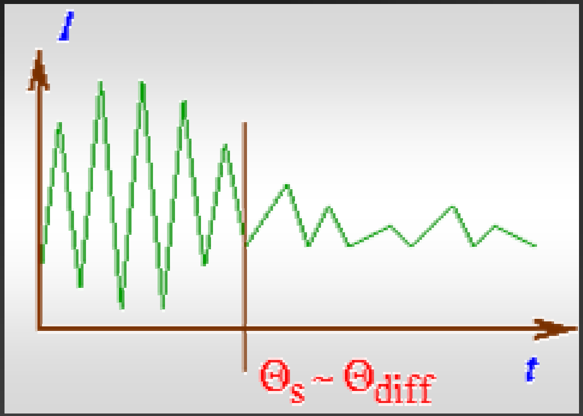
(Covino at al. 1999; Wijers et al. 1999)

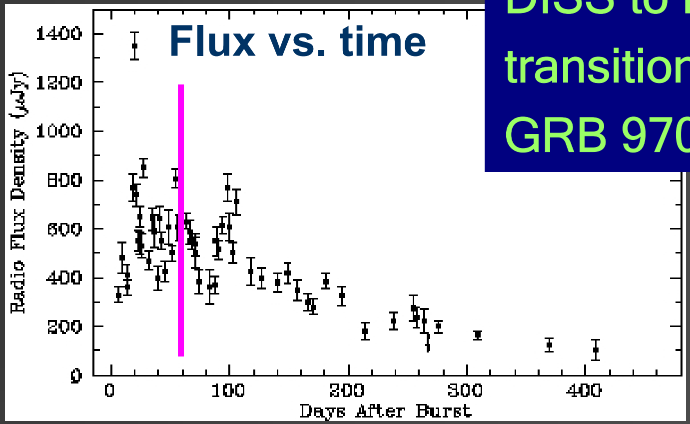
# Polarization Scintillation




(Medvedev & Loeb 1999; Medvedev 2000)

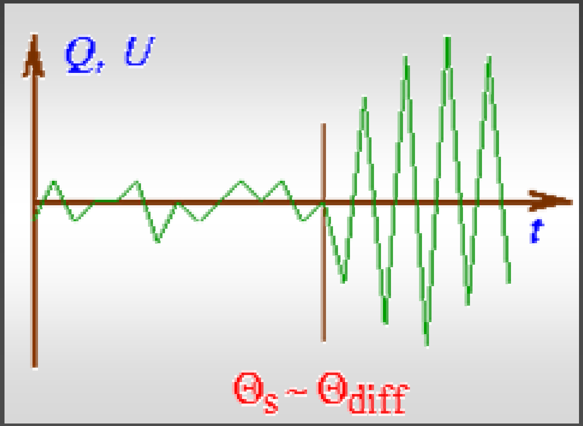
# Polarization Scintillatons of GRBs




DISS to RISS transition in GRB 970508

(Frail, Waxman, Kulkarni 1999)




**No detection yet;**

**upper limit : $< \pi > \ < \ 10\%$**

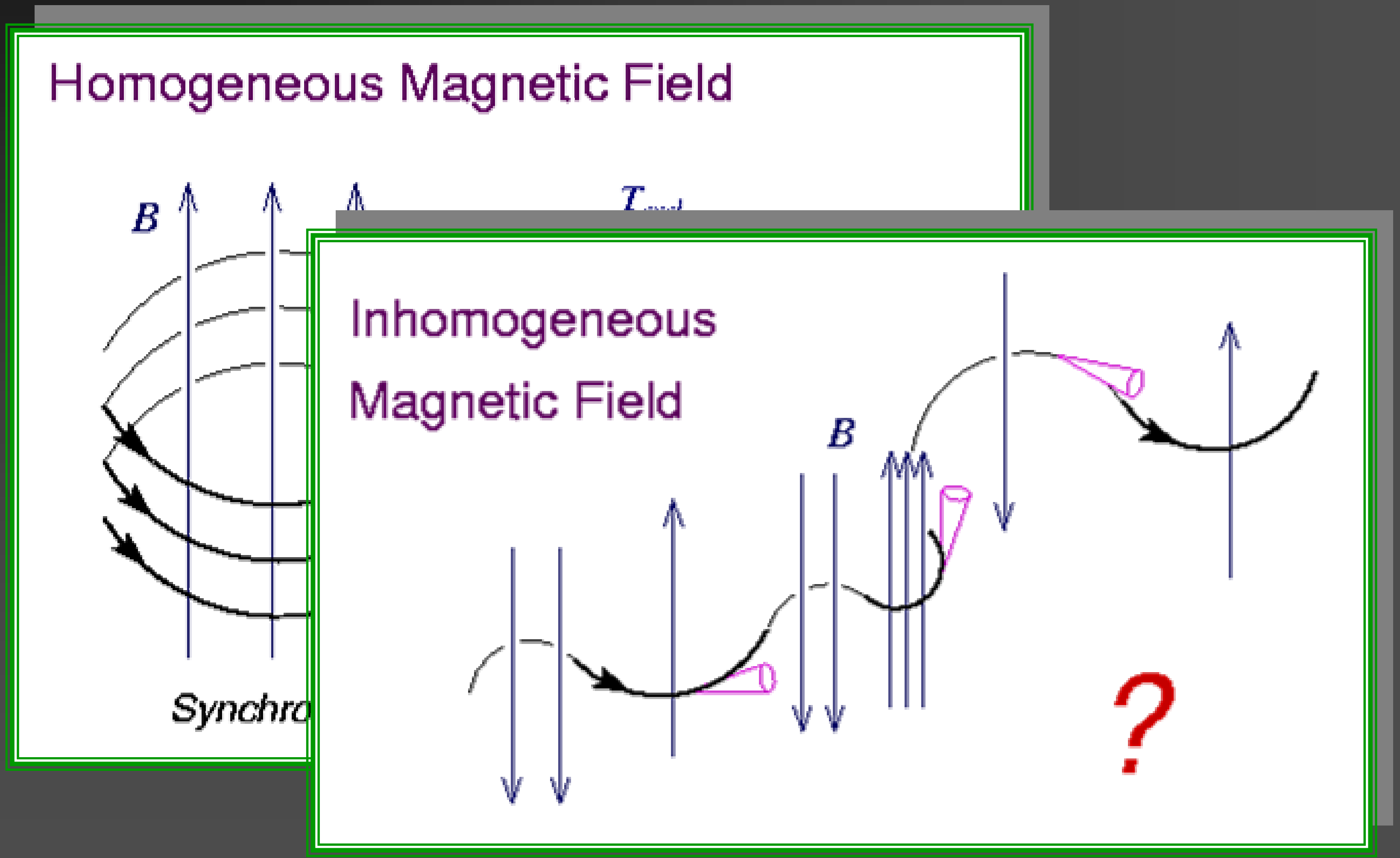
# Testing Theory

*Spectrum of radiation emitted by accelerated particles in a small-scale, tangled magnetic field*

~~synchrotron~~

jitter

# Synchrotron Vs. Jitter Radiation

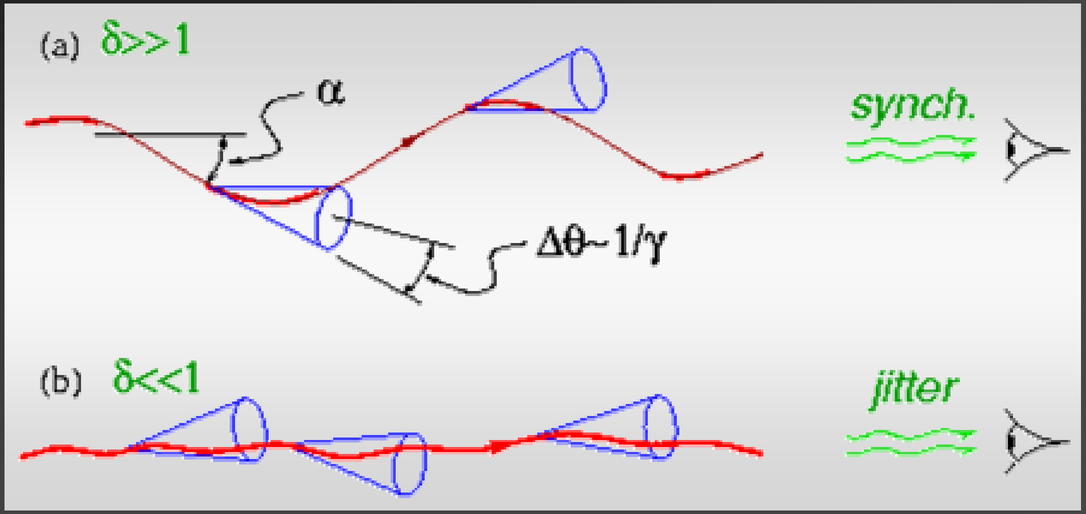



(Medvedev 2000, ApJ)

# Jitter Radiation

***Radiation from small-scale fields***

# Regimes




$\omega_s \sim \gamma^2\, \omega_H$

$\omega_j \sim \gamma^2\, c/\lambda$

$$\boxed{\delta = \frac{\alpha}{\Delta\theta} = \frac{eB\lambda}{mc^2}}$$

… independent of γ !

# Jitter Radiation. Theory

- *Ultra-relativistic* $e^-$: velocity $\mathbf{v} \simeq const$, acceleration $\mathbf{w} \equiv \dot{\mathbf{v}}$ varies
- Liénard-Wiechart potentials
  $\to$ total energy emitted per unit solid angle per unit frequency:

$$dW = \frac{e^2}{2\pi c^3}\left(\frac{\omega}{\omega'}\right)^4 \left|\mathbf{n} \times \left[\left(\mathbf{n} - \frac{\mathbf{v}}{c}\right) \times \mathbf{w}_{\omega'}\right]\right|^2 d\Omega \frac{d\omega}{2\pi}$$

  Here $\omega' = \omega(1 - \mathbf{n} \cdot \mathbf{v}/c)$, $\mathbf{n}$ points to the observer, and $\mathbf{w}_{\omega'} = \int \mathbf{w} e^{i\omega' t}\, dt$.
- Integrate over $d\Omega \simeq \theta\, d\theta\, d\phi$ with $\theta \sim 1/\gamma$, $0 < \phi < 2\pi$:
- Ac
- Ma

- Spectral power: $P(\omega) = dW/(T\, d\omega)$:

$$P(\omega) = \frac{e^2}{2c}\delta^2 \frac{\omega_j}{\gamma^2} \frac{\bar{B}^2_{SS}}{\bar{B}^2_e} J\left(\frac{\omega}{\omega_j}\right),$$

  where

$$\omega_j = \gamma^2 k_{Be} c = 2^{7/4} \gamma^2 \gamma_{\rm int} \bar{\gamma}_e^{-1/2} \omega_{pe},$$

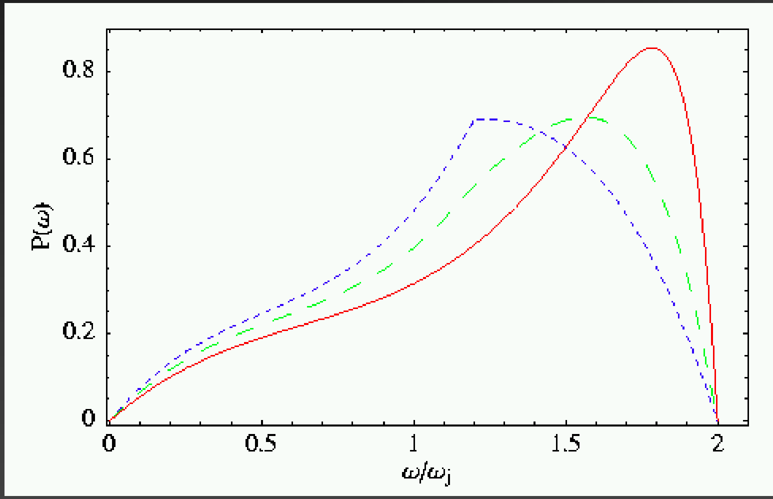
  and

$$J(\xi) = (2\mu+1)\xi^{2\mu}\left[I(\min[2;\, \xi/\delta]) - I(\xi)\right], \quad I(\xi) = \int \xi^{-2\mu}\left(1 - \xi + \xi^2/2\right) d\xi$$

- Total emitted power:

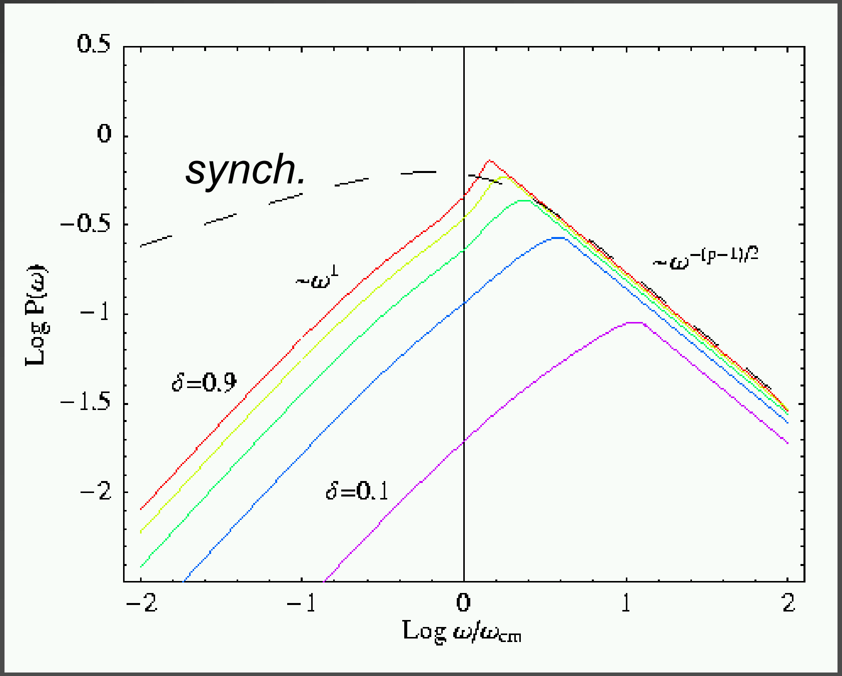
$$dW/dt = (2/3) r_e^2 c \gamma^2 \bar{B}^2_{SS}$$

# Jitter Spectra ( $F_\nu$ )




**Single electron**

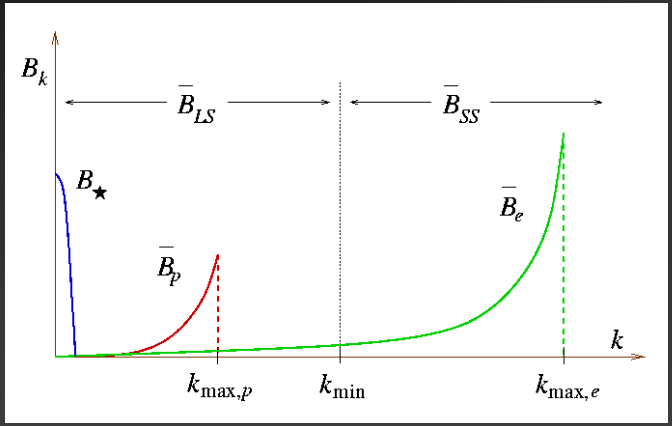
**Power-law electrons**

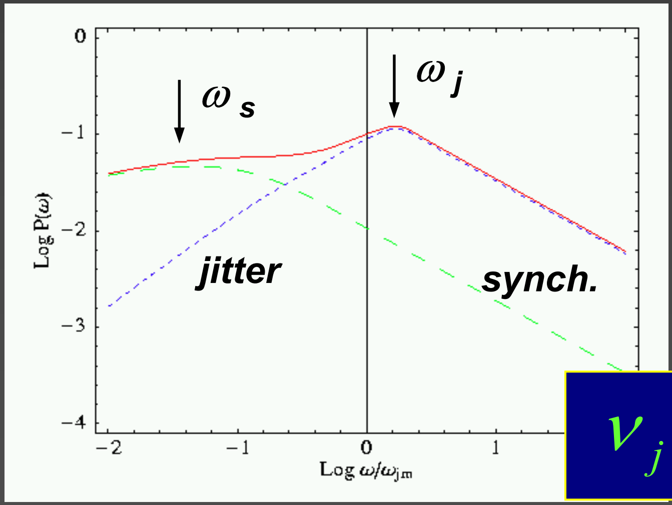



$B_k \sim k^{\mu}, \quad 0 < k < k_{\max,}\ \mu > 1$

$N(\gamma) \sim \gamma^{-p}, \quad \gamma > \gamma_{\min}$

# Composite Model of GRB Spectra




**Frequencies**

$$\frac{\omega_j}{\omega_s} = \frac{3}{2}\frac{B_{SS}}{B_{LS}}\delta$$

**Fluxes**

$$\frac{F_{J,\max}}{F_{S,\max}} = f(p,\mu)\,\delta^2$$

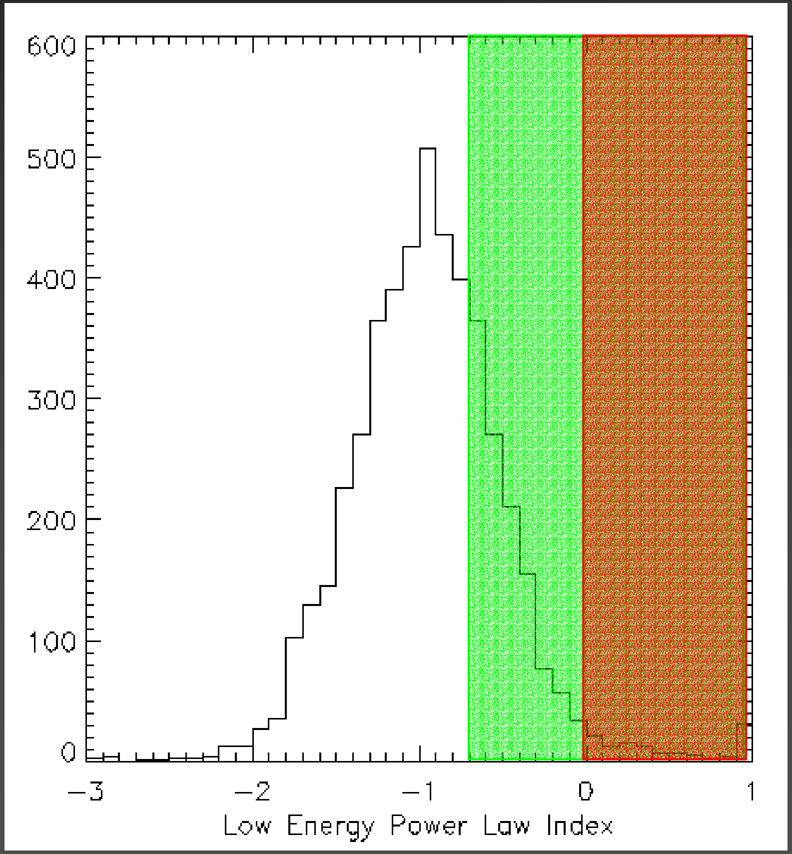
$$\delta \approx \sqrt{\varepsilon_B}$$

**Break**

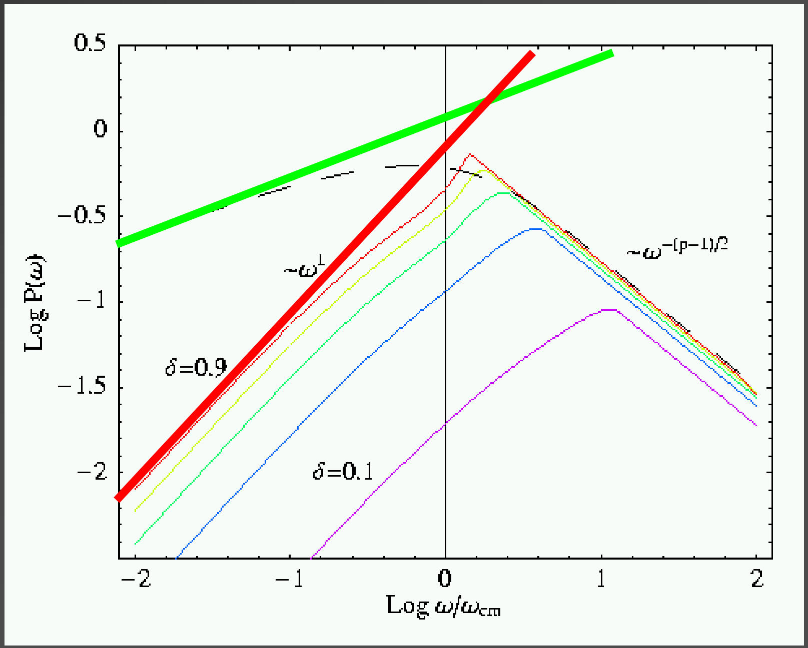
$$\nu_j \approx 6\times10^9\,\gamma_{\min}^2\,\Gamma_{\rm sh}\,\Gamma_{\rm int}\,\bar{\gamma}_e^{-1/2}\,n_{e,10}^{1/2}\ \ \mathrm{Hz}$$

# Synchrotron "Line of Death"

**About 30% of BATSE GRBs and 50% of BSAX GRBs have photon soft indices $\alpha$ greater than –2/3, inconsistent with optically thin Synchrotron Shock Model**




$F_\nu \sim \nu^\alpha$

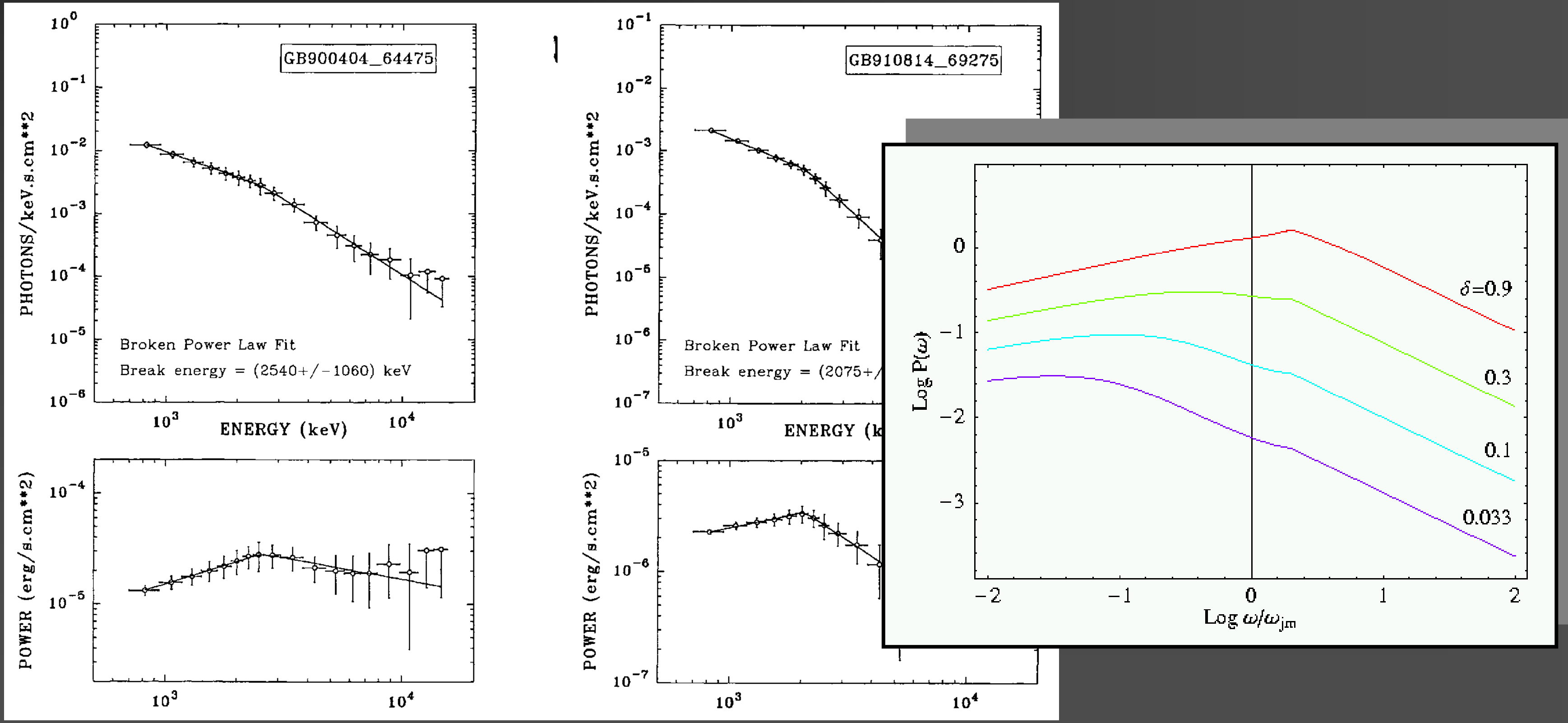



(Preece, et al. 2000, ApJS)

# “Broken Power-Law” Bursts

**Many bursts are:**

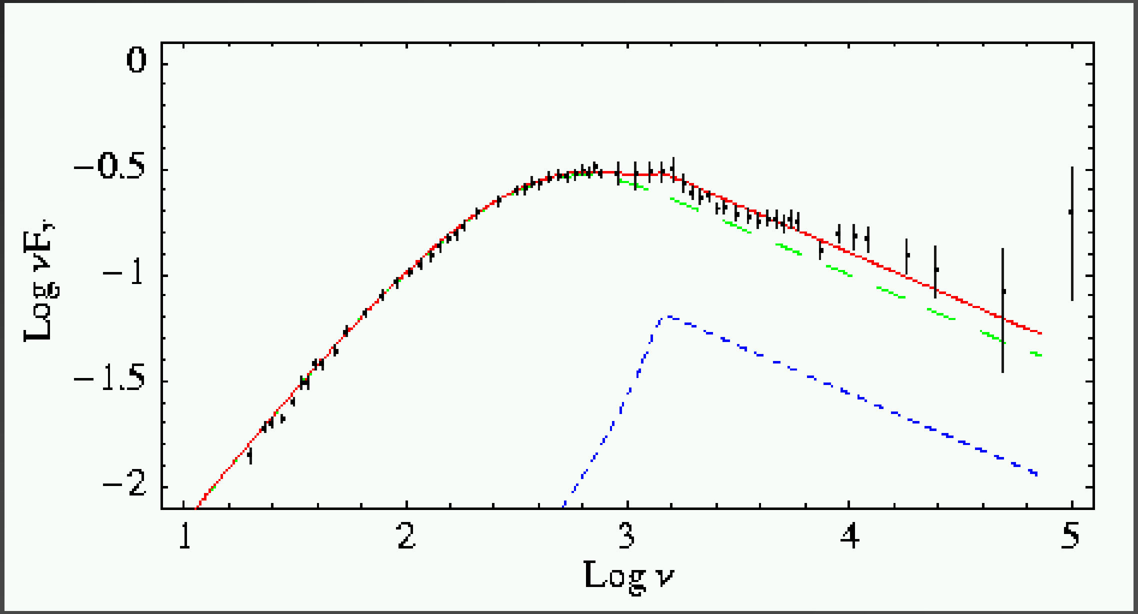
- better fit with a BPL spectral model
- inconsistent with a broad Synch. peak



# “GRB Lines”

Emission features: ~ 10 highly significant line candidates out of 117 GRBs

GRB 910503




- ✓ Spectral shape fit: $(B_{LS}/B_{SS})^2 = 7, \ \delta = 0.07$
- ✓ Deduce $\varepsilon_B = 4.\ 10^{-4}$ (consistent with $\varepsilon_B << 10^{-2}$; no cooled electrons)

# More tests to do…

- correlation of $\alpha$ with a spectral model

  *GRBs with larger* $\alpha$ *(i.e. violating LoD)*

  *may be better fit with the BPL model (sharper break)*

- look for emission features near $E_p$

  *if they exist, determine* $\delta$ *and other parameters*

- spectral model evolution in time

- are short bursts BPL or BAND?

# Conclusions

- **Theory of Collisionless ultra-relativistic shocks**
  - *explains origin of Magnetic Field*
  - *validates MHD for the shocks*
  - *predicts / explains Polarization detection*
  - *predicts Polarization Scintillations*
  - *predicts novel **Jitter radiation***
    - explains “Line of Death” violation
    - explains nature of BPL spectra
    - explains “GRB Line” emission features
  - *provides a way to study conditions in a fireball*